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THE VEGETATIVE PROPAGATION OF COFFEE

F. P. FERWERDA

(*Bangelan, Malang, Java*)

VEGETATIVE propagation of coffee has been applied to plantation practice in Java for some fifty years. In the course of that half century the method has excited the keenest interest, only to be almost forgotten later, and now it has entered into favour once again. Thus three epochs can be distinguished in its history: the first from 1887 until about 1908, the second from 1915 to 1930, and the third from 1930 to the present day. These three periods will be considered in order, but it will be necessary first to describe the methods of vegetative propagation.

I. *Methods of Vegetative Propagation*

Of all the possible methods of vegetative propagation, grafting alone has found practical application. Setting, layering, and budding succeed fairly well, but so far as is known are little used.

Coffee was first successfully grafted in 1887 by van Riemsdijk by whip grafting [1], the operation being carried out in a pit, covered with a glass frame. As budwood, either a section of a water-shoot or an ordinary lateral branch was used, and, as in fruit trees, it was joined on to a stock of the same thickness. The budwood and stock were bound tightly together with a soft binding material. Grafting wax was not used. At the present time this method is still used occasionally. Experience has shown that it is not necessary to graft under glass; it can easily be done in the open under light shade, provided that the graft is prevented from drying up by covering it with a wide test-tube or casing of water-tight paper. The wrapping can be removed after a month.

A second method of grafting is cleft-grafting, first used by Butin-Schaap [2, 3, 4, 5]. A strong, sprouting water-shoot which is just becoming woody is cut into sections through the approximate centre of each internode. Two or three sections from the middle of the shoot yield suitable budwood; the two end sections are less suitable. Budwood of about the thickness of a stout lead pencil ($\frac{3}{4}$ cm.) is the best, though this is, of course, only an approximate measure, as some clones will yield thick, others thin water-shoots. To graft, the lower end of the twig is cut to a wedge shape with a razor-sharp knife, taking care that no dirt falls on the wounded surface. A stock of about the same thickness as the grafting twig is selected, cut off at about 20 cm. above soil-level, and split longitudinally for 3–4 cm. The wedge-shaped twig is then inserted into the slit so that scion and stock fit exactly. The graft is tied round with binding, but grafting wax is not used.

Cleft grafts can be made equally well under glass or in a covered nursery, and good results can even be obtained in plantations. For the first three or four weeks the grafts should be protected against drying out by means of an inverted test-tube or a sheath of parchment paper.

Of these two methods the latter has been found by far the most

practicable; growth is so good that after six months the grafting place can scarcely be detected. An experienced grafter can conveniently make 100–150 grafts a day, of which from 75 to 90 per cent. are successful in good, i.e. dry, weather. In both methods either water-shoots or lateral branches can be used for grafting. Until recently preference was given to the former, which give normal growth, whereas grafts of lateral shoots usually produce flattened shrubs with prostrate branches. This is a result of the very marked polarity of coffee.

Latterly, experience has shown that grafts from upward-growing lateral branches of selected mother-trees can be obtained having a form intermediate between the two described above. They are described in some detail by Hille Ris Lambers [6]. Some of the clones thus obtained are remarkable for their very strong development, their great productivity, and slight susceptibility to attacks of the dreaded branch-borer (*Xyleborus* sp.). Great expectations are entertained of these clones, although they have scarcely yet been tested out.

For the sake of completeness, a third method of vegetative propagation may be mentioned, which was occasionally used on a fairly large scale about thirty years ago. In this last method, called nurse-grafting or twin-grafting, a surface wound is made in the stems of young (8-months-old) plants, or even of quite small seedlings, which are then bound together in pairs with the wounded surfaces in contact. As soon as growth is established, one plant is cut through below the junction so that it remains attached to the root of the other plant, the top of which is then removed, thus making a graft. This rather cumbersome method is suitable for getting grafts of *arabica* on *liberica* stocks. Its chief disadvantage is that one is dealing not with real clones but with seedlings grafted on to other root-systems.

To make the review complete, mention should be made of budding, although, as far as I know, it has not been used in Java. In the Philippines, however, it has been successful [7]. Very recently, experiments have been made in Java on the setting, layering, and cutting of coffee plants. These have not yet produced results applicable to practice.

The anatomy of grafting has been exhaustively studied by Zimmermann [3] and de Haan [5]. At the junction a callus develops from the stock, and a cambium differentiates forming a connexion between the cambia of the stock and graft. The connexion is complete in about three weeks, after which growth commences.

II. *Advantages and Disadvantages of Vegetative Propagation*

The advantages and disadvantages of vegetatively-propagated coffee were first defined by Cramer [8]. The most important advantage is undoubtedly that the daughter-individuals produced exactly resemble in outward appearance both one another and the mother-plant. It is thus possible to multiply species hybrids which, when propagated by seed, always yield an extremely variable and poor progeny. Since these species hybrids include some very valuable types of coffee, the importance of this aspect of vegetative propagation is clear.

The similarity among the vegetative offspring from one mother-plant has several advantages, of which the most outstanding are:

1. *Uniformity of habit.*—Grafts belonging to one clone are externally similar. In this respect they differ from seedling-strains, among which very great variations are usually encountered.

2. *Uniformity in size of berry and bean.*—Grafts belonging to one clone yield a very homogeneous product, showing very little variability in the size of berries and beans. This characteristic can be seen by ocular inspection, and it becomes obvious when the sizes and weights of the beans are measured, and the figures treated statistically. By using different clones which yield beans of equal size it is thus possible to obtain a uniform produce not requiring any appreciable grading. This uniformity is also very advantageous in the preparation of coffee, especially in the case of *C. excelsa* and *C. arabica*, seedlings from which yield berries of very varying sizes, causing difficulties in crushing. This difficulty is avoided by using clones which produce berries of approximately equal size.

3. *Simultaneous cropping of grafts from one mother-tree.*—Analogously to fruit crops, coffee clones may be distinguished as early—or late—ripening. Thus *robusta* clones are known to us from which 70 per cent. of the total harvest has been collected between April and June, whereas from other clones only 17 per cent. of the harvest is obtained in the same period. These data are based on figures of production for ten consecutive years.

The significance of this is clear; if plantations are made from clones of different ripening periods, it should be possible to control the harvesting time so that it is spread evenly over a larger number of months. This is especially important on estates which have difficulty in providing for large numbers of employees, or are inadequately equipped by reason of a limited drying capacity.

The narrowly restricted ripening period of clones also enables a more efficient attack to be made on the berry-borer beetle. If a plantation is arranged so that all the beans can be harvested more or less simultaneously, the berry-borer will be deprived of food for several months and the pest can thus be confined to very narrow bounds.

4. *Possibility of obtaining economic coffee plantations on nematode-infected soils by means of grafts on resistant stocks.*—This idea was the basis of the original tests with coffee grafts, and in recent times particularly, the problem has come to the fore since strong evidence has been obtained that stocks do indeed exist which are little, or not at all, susceptible to nematodes.

5. *The possibility of improving existing seedling-plantations by top-working inferior plants.*—Even the most carefully selected strains contain 10–25 per cent. of 'non-valeurs', producing practically no crop and thereby reducing the average yield per tree of the plantation. If top-worked with budwood from high-yielding clones, these poor-yielding seedlings can be converted into valuable grafts, considerably improving the plantation.

There are naturally several drawbacks which tend to offset the above-

mentioned advantages. The greatest practical drawback which restrains the planter from large-scale grafting is undoubtedly the cumbersomeness of the method. For example, if a graft plantation is to be established by the end of 1935, the seeds must be set in July 1934, in order that the necessary stocks will be ready in July 1935. Further, care must be taken over the growth of the necessary budwood, and there is finally the difficulty involved in the weakness of a young graft which demands that more care should be devoted to it than to a seedling during and after its transplantation into the open. These drawbacks, however, should not be exaggerated; they are technical by nature and they can all be overcome by good organization and careful planting. Every intensification of cultural methods inevitably demands that care and trouble should be taken over it.

III. *Vegetative Propagation of Coffee in Practice*

1. *The period 1887–1908.*—This period includes the time when the continually spreading Hemileia leaf-disease and the increasingly acute nematode pest brought ruin to the thriving culture of *arabica* coffee. A desperate search for some means of procuring even a small profit from coffee plantations ensued, and it was believed that the remedy had been found in the grafting of *arabica* on to *liberica* stocks. It had been noticed that *liberica* with its stronger root-system had suffered less from nemas than *C. arabica*; and it was hoped that grafts of *C. arabica* on *C. liberica* would also thrive on nematode-infested land; it was also expected that the graft would be stronger and thus offer greater resistance to leaf-disease.

Van Riemsdijk was the first to make coffee grafts with this object in view, but without much success [1]. The grafts certainly suffered less from nematodes, but their productivity was low, and their susceptibility to leaf-disease was scarcely reduced. More promising were the *liberica-arabica* hybrids arising from spontaneous crossing, which were resistant against leaf-disease. Multiplication by seed was impossible on account of the very heterogeneous progeny obtained from the hybrids. Again it was van Riemsdijk who realized the importance of such hybrids and propagated the so-called Kalimas hybrid vegetatively by grafts taken from lateral branches. Considerable areas were planted with these grafts which, on account of the marked polarity of coffee, developed into squat bushes ('pancakes') with their branches trailing along the ground. Although their productivity was not high, and the quality of the product was lower than that of *C. arabica*, and the output was poor owing to the high proportion of woolly beans, these grafts nevertheless saved the situation in many cases. In 1896 when the nematode plague became very acute, and the leaf-disease was coming more and more into evidence, a very marked revival of interest in grafting occurred. Several estates established graft plantations, both of *arabica* and of *arabica-liberica* hybrids. Besides the Kalimas, other newly discovered hybrids, of which the Kawisari was the best known, were used.

At the beginning of this century, when leaf-disease was also ravaging *liberica* coffee, these grafts were successfully used to convert uneconomic

liberica plantations into productive hybrid complexes. Use was occasionally made in these conversions of *liberica* clones resistant to leaf-disease.

Notwithstanding the satisfactory results obtained with grafts and the wide advocacy given them in different quarters [9], grafting has never been really popular. The method was considered too cumbersome, was obviously not really to be trusted, and was only adopted as a last recourse. When *robusta* coffee was introduced into Java in the first decade of this century, it was taken up enthusiastically, for not only was it (at least at first) immune from leaf-disease and scarcely suffered from nemas, but above all it was easily multiplied from seed. Interest in grafting declined completely, and did not revive again until 1915.

2. *The period 1915–29.*—It was Cramer [8] who infused new life into this forgotten and unappreciated method. When, in 1915, he was in charge of the selection work at the Government Coffee Station 'Bangelan', he made the problem of vegetative propagation in its widest sense the central point of his programme. He realized that selection, particularly of perennial crops, would produce the quickest results when vegetative and generative progeny were tested simultaneously.

In order to do this, both seedlings and grafts were raised from each suitable mother-tree so that both types of progeny could be studied. Preliminary experiments with clones were made in small plots—'museum plots'—of 16 or 49 trees, using *C. excelsa* almost exclusively as root-stock. The most promising clones were afterwards transplanted into large plots about a hectare in area which served as seed-gardens as well as testing fields for clones. All these plots of grafts developed excellently, and the stands, as might be expected from grafts, were very uniform in every respect. They yielded heavily in the third year after planting out, in contrast to seedlings of similar age from the same mother-trees, which did not bear appreciable fruit before the fourth year. These good yields persisted for the first two or three productive years, but afterwards, at any rate in the large monoclone plantation, the yields fell off more and more, in proportion to the age of the plantation. At an age of 8 years the mean yield of the grafts was only 50–60 per cent. of that of the seedlings of equal age.

An explanation had to be found of this remarkable, though disappointing phenomenon. Cramer [10] thought that the cause lay in the *excelsa* stock, on which nearly all the grafts were made. Consequently, extensive tests were made in 1924 by grafting the most promising clones on *robusta* and *robusta*-like, as well as on *excelsa*, stocks. For stocks, the most uniform material obtainable at that time was used, i.e. seedlings grown from seed harvested from the middle of large monoclone blocks, and therefore mainly self-pollinated.

The following observations were made on the different combinations of clones and strains used as root-stock:

(1) Determination of the percentage of successful grafts made in the nursery.

(2) Determination of the percentage of grafts that died after being planted out in the open.

(3) Study of growth by periodical measurements of height.

(4) Observation of the time on which the first flower-buds appeared.

The following conclusions were drawn from these observations:

(*a*) Grafting is easy with some clones, difficult with others. Hybrids are typical of the former class, and most *excelsa* clones of the latter.

(*b*) It often happens that a clone that does well and develops perfectly on one root-stock strain will fail on another.

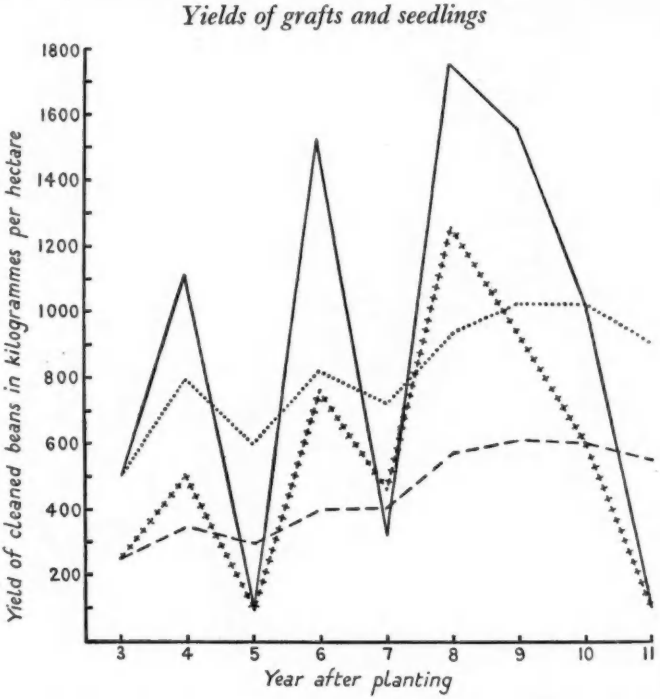

FIG. 1. Yields of grafts planted in big monoclonal blocks compared with those of seedlings from the same mother-trees and of the same age. Conditions of soil are comparable.

——— = seedlings, yields per year.
..... = ,, average yield up to the indicated year.
++++++ = grafts, yields per year.
– – – – – = ,, average yield up to the indicated year.

(From Ferwerda [11].)

(*c*) There are some universally good stocks on which the most divergent kinds of clone succeed, grow quickly, come early into bearing, and, in short, do well in every way. Such a stock is *robusta* Bgn. 124–01, which is very satisfactory with a number of *robusta* clones, as well as with *liberica-arabica* and *uganda-congensis* hybrids.

(*d*) On the other hand, there are strains which are unsuitable as stocks for several clones, e.g. *robusta* Bgn. 59, on which three different clones

took badly, yielded 30–50 per cent. of failures when planted out, and were always backward in development.

(*e*) In general, grafts come into bearing earlier than seedlings. Cases have been cited of 2-year-old graft plantations bearing fruit on more than 80 per cent. of the trees, whereas only 15 per cent. of the trees grown from seed bore fruit at that age.

Following these extremely significant results, the yields that would be obtained from the different combinations of clone and stock were eagerly awaited, since it is these that must form the ultimate basis of practice. After the different combinations—which were all planted out in monoclone blocks—had been bearing for some years, the disappointing conclusion was reached that these grafts were also yielding very poorly; comparison with sown plants of similar age showed that the latter yielded four times as much as the grafts [11]. In spite of the much deeper insight gained from these experiments into the mutual compatibility of clones and stocks, the development of the established grafts, and the time of bearing, the greatest disadvantage of coffee grafts—their poor yields—remained. The experiments had failed to solve this problem of the vegetative propagation of coffee, and further research had to be directed along entirely new lines.

3. *The period from 1930 onward.*—Experience gained in fruit culture, where the same kind of difficulty had been encountered, eventually showed the way to the solution of the problem. Orchards planted with one kind of clone displayed a magnificent and uniform appearance but produced no fruit. Careful research indicated that most fruit trees are markedly self-incompatible, and since self-pollination necessarily predominates in monoclone blocks, the setting, and consequently the yield of fruit in them, is poor.

The poor yields from coffee grafts planted in monoclone blocks can probably be traced to the same cause [11]—a hypothesis that is supported by the following facts:

(1) Fruit will not set, or only badly, on most varieties of coffee, with the exception of *C. arabica*, when they are self-pollinated [12, 13, 14, 15, 16]. Ferwerda [11] found in 1930 that not more than 0·5 per cent. of the fruit set on artificially self-pollinated *robusta* clones, whereas on artificially cross-pollinated clones 30–50 per cent. set. The more recent work of Hille Ris Lambers [16] and Ferwerda [17] has demonstrated that this behaviour is common to practically all *robusta* clones.

(2) It is evident from observations that the amount of fruit setting under natural conditions in plantations of monoclone grafts is much less than in seedling-plantations under similar conditions. In a series of 3-year experiments, Ferwerda [11] found that whereas the average amount of fruit setting on grafts was 5 per cent., it was 13·5 per cent. on seedlings, i.e. fully twice as great as on grafts planted in monoclone blocks.

(3) In monoclone-graft plantations, the yield of fruit falls off steadily from the outside inwards. The outermost rows yield 2–3 times as much as those in the centre of the plantation [17].

(4) Fruit sets much better in small than in large monoclone-graft plantations [11].

(5) Small graft-plots yield quite well, even when planted with clones which yield badly in large monoclone blocks [11].

These facts make it highly probable that the poor yields from grafts in large monoclone-plantations is a consequence of the absence of cross-pollination. Hence to obtain a profitable graft-plantation, satisfactory cross-pollination must be secured by using an appropriate mixture of clones, fulfilling the following conditions:

(i) the clones in the mixture must flower simultaneously;
(ii) the clones must be inter-compatible.

Graph indicating fruit-fall in grafts planted monoclonal, compared with that of seedlings from the same mother-trees

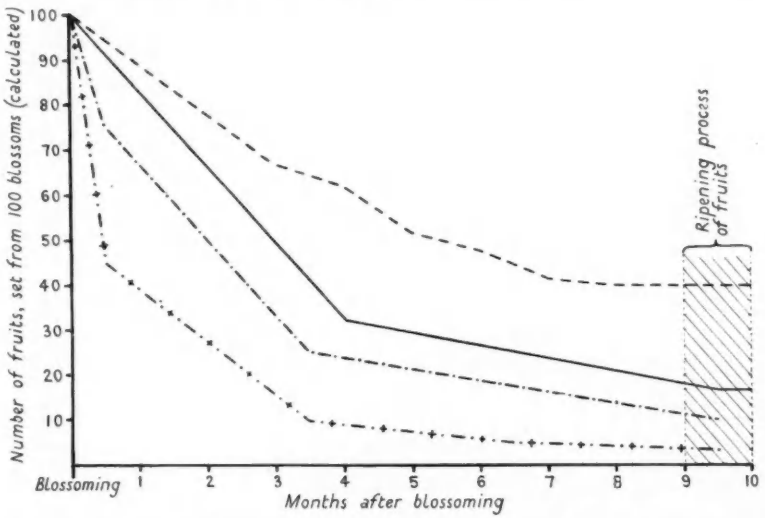

FIG. 2. Fruit-fall in grafts and seedlings of *Robusta*. At fixed intervals the number of fruits still alive was estimated and calculated per 100 flowers. In grafts planted in big monoclonal blocks the fruit-fall is about twice as large as that of seedlings.

——— = Seedlings, 1930–1931
·+·–·+· = Grafts, 1930–1931
– – – – – = Seedlings, 1932–1933
–·–·–·– = Grafts, 1932–1933

The first of these points requires particular attention. Nearly all coffee varieties have a sharply defined flowering period that is completed in about two days, and if the mixed clones do not flower simultaneously, there is no chance of their mutual pollination, and the whole effect of mixing them is lost. Observations of the flowering rhythm have shown, however, that, although there are some notable exceptions, most of the usable clones flowered almost simultaneously [18].

The second point, concerning the mutual fertility of the clones, has been studied by Ferwerda [11, 17] and Hille Ris Lambers [6]. Both

Graph indicating decrease of yield in monoclonal blocks from outside to inside

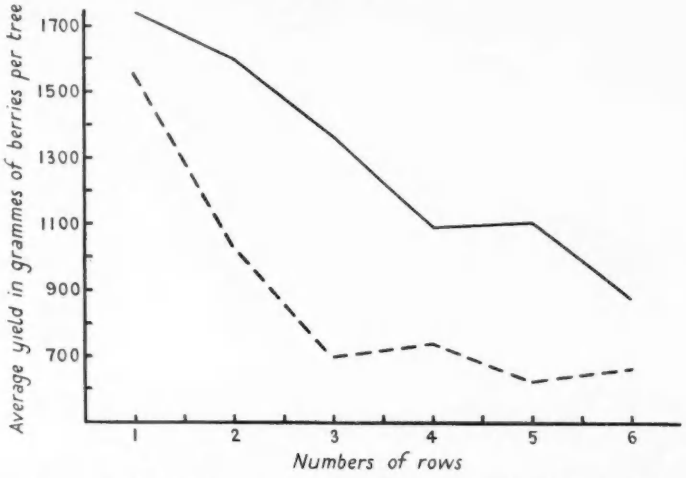

FIG. 3. Decrease of yield from outside to inside of monoclonal blocks. The rows of trees are marked 1–6. No. 1 is the exterior row, no. 6 the interior row.

——— = Clone *robusta* Bgn. 124
– – – – – = ,, ,, ,, 59

workers found that the mutual cross-pollination of nearly all the known *robusta* clones resulted in good fruit-setting. It was further found that certain combinations were occasionally unsuccessful, e.g. *robusta* S.A. 109 × *robusta* S.A. 13 [16], and *robusta* Bgn. 59.01.01 × *robusta* Bgn. 105. The latter combination has failed for three years in succession [17]. In contrast to fruit crops in which intersterility is usually reciprocal, this phenomenon in coffee has so far only been observed in one direction. Investigations on self-incompatibility and cross-fertility have also been made with other varieties besides *Coffea robusta*. Among the *congensis* hybrids, some appear to be self-incompatible [16, 17]; the others produce quite good fruit-setting by self-pollination. With *liberica-arabica* hybrids, fruit-setting is generally equally good with self- as with cross-pollination [17].

The main conclusion to be drawn from these investigations is that the best results are to be expected from a mixture of, say, five suitable clones, or of clones and seedlings. Experiments have been set up to confirm this hypothesis. The preliminary yield-data from mixed-clone plantations are promising; instances have been observed in which clones in mixed plantations have produced 1½–2 times as much as in monoclone blocks [17].

It should be mentioned in this connexion that grafting can be used as a cultural measure to improve seedling-plantations. In this method, which was used thirty years ago in *liberica* plantations (cf. pp. 192–3), runners are raised from all the poor yielding trees, or those badly attacked

by the branch borer (*Xyleborus* spp.), and are top-worked as soon as they have reached a suitable age. When the graft is successfully established, the old tree is sawn off above the grafting place, and a valuable, well-growing graft is thus obtained in place of an inferior seedling. The method has

Diagrams showing grades of compatibility between certain clones of robusta *coffee*

A

♀↓ ♂→	S.A. 34	S.A. 56	S.A. 85	S.A. 142	S.A. 158
S.A. 34	**5**	84	33	63	82
S.A. 56	63	**3**	91	78	79
S.A. 85	43	78	**6**	51	69
S.A. 142	37	44	45	**10**	60
S.A. 158	85	69	79	81	**1**

B

♀↓ ♂→	Rob. Bgn. 78–11	Rob. Bgn. 105–03	Uganda Bgn. 2–01	Uganda Bgn. 3–02
Rob. Bgn. 105	34	46	56	82
Rob. Bgn. 105–03	31	<**5**	47	**5·5**
Rob. Bgn. 202	69	55	68	68
Uganda Bgn. 3–02	41	36	53	<**5**

FIG. 4. These tables indicate the pollination-requirement of certain *robusta* clones. The figures indicate the number of half-grown (A) or full-grown (B) fruits obtained from 100 flowers. Percentages of success of self-pollinations are printed in bold type. A. from Hille Ris Lambers [6], B. from Ferwerda [17].

been used on a large scale on some estates in East Java, to such an extent that sometimes 30–50 per cent. of the plantation finally consisted of grafts. The results have been excellent and sometimes a yield increase of 60 per cent. has been obtained [19]. The good productivity of the grafts is easily explained by the fact that they are placed among seedlings, they have favourable conditions for cross-pollination, and the fruit consequently sets well.

When it is remembered that even in carefully selected lines quite a large number of poor specimens may occur (cases are known where 75 per cent. of the total yield has been produced by 47 per cent. of the trees [11]) it will be clear that a good deal can be achieved by top-working bad yielders. The safest course is to use clones that have already been tested. The planter may easily be disappointed if he uses shoots from the best trees in his own plantation, for by no means every good tree yields a good clone; even the contrary is often true.

IV. *The Future of Vegetative Propagation*

Interest in vegetatively-propagated coffee has greatly increased during the last year or two, partly because the former drawbacks which discredited the use of coffee grafts have largely been overcome. Furthermore, the spreading pest of leaf-borers and the still unchecked nematode pest have also contributed to the awakening interest in coffee-grafting. In the immediate future, grafting will be used as a cultural measure for the improvement of existing seedling-plantations. It is difficult to say whether water-shoots or lateral branches will be preferred for grafting. Later on, when the full data regarding mixtures of clones have been collected from the experimental plantations, clonal mixtures will certainly find acceptance. Only then will the advantages of vegetatively-propagated plants be fully appreciated, but whether grafts will ultimately replace the seedlings now in common use is a question which the future alone can answer.

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EARLY EXPERIMENTS ON GRAFTING COFFEE IN JAVA

P. J. S. CRAMER

ALTHOUGH the propagation of coffee by grafting had been studied with success by old, experienced planters in Java prior to 1914, it was in that year that extensive work on this method was first undertaken. When I started working in Java I soon realized that material improvements in the cultivation of such tropical crops as coffee, rubber, and cacao would have to be based upon two fundamental corner-stones. The first was selection from the wild plant. The productivity and other valuable characters of wild forms must be studied under close observation in experimental fields; and new characters can only be introduced into our cultivated plants by hybridization from selected wild plants. When the first plants of our present crop were taken into cultivation, proper attention was very seldom paid to their hereditary character and to selecting the really best for the purpose. The second corner-stone of improvement was the study of vegetative propagation, which up to 1914 had been little used, although it had long been practically the only method in use for permanent cultivations in countries where agriculture was more developed, like orchard crops in Europe and North America and citrus in Japan. Looking backwards and recognizing all the defects and false starts in our early work, there is no doubt that these two considerations —the introduction of new species, varieties and hybrids, and the greater use of vegetative multiplication—are of fundamental value in obtaining the improvements that the botanist is aiming at, viz. increase of yield, improvement of quality, protection against disease, and, in the sequel, lowering of production costs.

Curiously, the earliest attempts to introduce grafting into the technique of coffee-growing were not primarily designed to increase yield, but to combat a pest. In the year *c.* 1895, cultivators were somewhat alarmed by the trouble caused by nematodes attacking the roots of their coffee plants (then almost exclusively *C. arabica*). The most common species was *Tylenchus coffeae*, but only *arabica* suffered heavily from it, *C. liberica* remaining practically unscathed. Other species of nematodes, e.g. *Tylenchus acutocaudatus*, were found later attacking both species, but in those days they do not seem to have caused so much damage as *T. coffeae*. Following the well-known example of grafting French vines on resistant American stocks to overcome phylloxera, planters sought a similar remedy against nematodes in coffee. Butin-Schaap, a planter in Central Java, succeeded in grafting *C. arabica* var. Maragogipe on *liberica* stock, but apparently without lasting success. This variety, which was originally found in Brazil, probably as a seedling mutation, bears large broad beans of excellent flavour, but the yield is very small, an acre of it often giving only a few handfuls of market coffee. Schaap's successful experiment did not develop into a practical method; large fields of Maragogipe grafts were never laid out, probably because the grafting of *arabica* on *liberica* is too difficult an operation and the percentage of ultimate success is too low.

In 1889 a planter on the Kalimas estate in Central Java found in his nursery, probably among some seedlings of Liberian coffee, a plant which was much more vigorous than its neighbours; apparently it was a hybrid of *liberica* with *arabica*. There was nothing improbable in this, as Liberian coffee was introduced into Java at the end of the seventies and was often used to fill open spaces in old fields of *arabica*. The plantation manager who found this hybrid was much interested in it, planted it out near the assistant's house, and used all the seeds for his own garden. The manager of a neighbouring estate, Klein Getas, discerning a future for the new kind, and being unable to obtain seeds, asked for and obtained a few branches, which he grafted successfully. The owner of the original tree planted seedlings; but they turned out to be no good. We know now that hybrids of *arabica* and *liberica* give as a rule only poor seedlings, and that they offer very little scope for improvements. The planter who multiplied the branches by grafting—his name was van Riemsdyk—was quite successful; he grew fine, very productive trees and went on grafting, so that when I visited Klein Getas in 1906, several hundred acres of the Kalimas hybrid were in full production.

The story taught us something more. It induced us to develop a method of making coffee grafts on a large scale by keeping them in a moist atmosphere. This was usually done by raising them in a deep hole sunk in the earth and covering with a glass plate; nowadays we graft under glass tubes or tubes made out of waxed paper. This early experience also taught that if grafts are made of common dorso-ventral branches they will maintain this dorso-ventral habit of growth and develop into flat shrubs, which the planter used to call 'pancakes' or 'crows' nests'. If, however, the shoots on the main stem, with a radial habit of growth, are used, trees with normal branching will result. If 'adventive' branches are used, i.e. more or less upward-growing shoots developed on normal primary branches that usually grow somewhat obliquely to the supporting branch, a graft with a shrub-like growth is obtained. As already stated, van Riemsdyk made all his first grafts from branches. When I asked him why, he replied that grafts made with suckers from the main stem had a normal habit of growth, but they suffered more from leaf-disease than branch-grafts. I felt convinced that this explanation was based on an error and that van Riemsdyk, unable to obtain a normal sucker or top of a tree for making his grafts, compared branch-grafts of the hybrid with sucker-grafts (or top grafts as they are usually called) of *arabica*, and that the top grafts developed leaf-disease, not because they were made from suckers, but because the much more susceptible *arabica* was the kind used. I have since often tried to get material from the original tree on Kalimas and was once able to visit it, about 1917, and to cut a few suckers from it. Grafted in our experiment garden, they turned out to be much more susceptible to leaf-disease (*Hemileia vastatrix*) than the branch-grafts; the latter, however, are also not immune and may, after a heavy crop, lose all their leaves from this disease.

Another lesson taught by this old experience is that grafting is especially indicated for multiplying inter-specific coffee hybrids. The offspring of

coffee hybrids is always extremely variable, and when the parents are not closely allied species like *robusta* and Quillou it consists almost entirely of plants without value, so that with hybrids from distant species there seems to be no hope of obtaining fairly constant races that can be multiplied by seeds. On the other hand, however, these hybrids can as a rule be easily multiplied by grafting. To get a high proportion of successes by grafting, it would appear that one at least of the constituents of the vegetative union—graft or stock—should be a vigorously growing hybrid, which brings to the union its more plastic nature. Most of the coffee hybrids that we have handled could be easily propagated by grafting; for example, Maragogipe coffee is difficult to graft, but a hybrid of it with *robusta* is one of the easiest. We shall see later that a hybrid between closely allied species (*robusta* and Quillou) makes an excellent stock.

After the grafting of a *liberica-arabica* hybrid at Klein Getas, the same method was applied at a few other places. In *c.* 1900, four nursery plants, which were recognized as *liberica-arabica* hybrids, were found on Kawisari estate in East Java. They were propagated by top grafts, and at least two of them, Kawisari B and D, were used for some time in practical coffee-growing. Kawisari B has a less spreading habit than the D variety, and it has curiously curved leaves.

In 1914 began a second period. In that year the experimental station at Bangelan, East Java, started new work on practical problems connected with coffee-growing, including experiments on grafting, and these, unlike the experiments of the earlier pioneers, were not laid down to overcome a pest or to propagate a type which could not be multiplied in another way. We had remarked that in various coffee fields, especially fields of *liberica*, *robusta*, and *excelsa*, the trees showed striking differences in habit, resistance to disease, size and colour of fruits, shape and texture of the leaves, and so on; for the same tree these characters were constant, but between two individual trees the differences were sometimes so wide that they seemed almost to belong to different species. We also found very marked differences in productivity; for example, in an acre of *robusta* coffee, containing, say, 400 trees, many trees would yield far more than the average, whilst others were so far below it that they did not give sufficient crop to pay for their upkeep; they lived like parasites on the better class. Frequent inspections of the Bangelan fields convinced us that many of the trees were naturally good yielders and others naturally poor yielders. So the question arose: Could we not eliminate the poor yielders and make the good ones occupy the whole field? Several methods of solving the problem presented themselves: one was to use only high-yielding plants, and one of the most direct ways of doing this was to use grafts of a high-yielding tree, which, adopting Webber's useful term, we called high-yielding clones.

Our first task at Bangelan was to make a survey of the trees and ascertain their value as clones. A few years before we had started to keep individual records of the annual yields of the best producers; the quantity of ripe berries collected at each round of picking, the proportion of market coffee obtained, and so on, were registered in these records. When we began to choose our mother-trees for clonal multiplication we

found these records useful, but never relied entirely upon them. The botanist should never let himself be led by figures alone, but should use his brain and eyes for comparing characters and finding out more than a sheet of figures can tell. The total impression that a tree makes on the experienced man is at least as valuable as the tree record, for it provides information not only on productivity, which I used to call the primary character, but also on the secondary characters of disease-resistance, vigour of growth, and regularity of shape.

In 1915 several hundreds of small squares, each containing four rows of four trees, were planted on Bangelan with grafts, each square with grafts of one tree, so forming one clone. We chose this number of 16 because it is usually easy to obtain within a year enough grafting wood for making such a number of grafts from one tree. This new extension of the experiment garden was called the 'museum' field, as it was a living museum of all the various superior types of our plantings, where a visitor could see the principal characters which our trees possessed. This museum field has certainly done a great deal to familiarize visiting planters with the basal idea of grafting, and it has convinced them of the very wide range of variation in coffee, and of the utility of basing vegetative multiplication upon it.

Once the museum field had been laid out—and I need hardly add that it was extended every year with new types—we resolved to go a step further and extend the best clones of our collection. We believed that a field of grafts would give higher yields than a field of variable seedlings, but before being able to plant whole fields with grafts of our clones we had to multiply the grafts for getting sufficient quantities of grafting wood. Therefore in a second series we planted plots of 49 trees, choosing the most promising clones, and from these we developed fields of one hectare containing 1,111 grafts. These fields were primarily intended to test the method from the practical standpoint, as well as to produce seed-coffee. The experiment garden had developed a good sale of seeds of our best kinds of *robusta*, *excelsa*, &c., and this brought in a useful revenue to help us in maintaining the garden. In the years 1916–19 we not only made extensions but, after covering all expenses, we paid a nice sum into the Colonial Treasury and carried forward a part of the crop to the following year as a kind of reserve fund. In view of the sale of seed, which brought in annually some *fl.* 15,000 (£1,250 gold standard), we put seeds of large monoclonal plantings at the disposition of planters, so that they could be sure that if seeds of a certain clone had given them the most productive plantings they could always get more of the same intrinsic value.

New problems arose in the course of this work. When we started grafting we thought *excelsa* would be a good stock, as, coming from a region near the desert, it offered a good chance of being drought-resistant; it showed a vigorous growth and did well on sandy soils as well as on clay and loam, and from sea-level up to 4,000 ft. We found, however, that the growth of some of our best *robusta* clones, which did very well on other stocks, was unsatisfactory on *excelsa*, and that seedlings of a hybrid between *robusta* and Quillou, although variable in its seedlings,

made an excellent stock. It was curious to find that clones of *liberica* coffee and of hybrids of *liberica* with *arabica*, although apparently more closely allied with *excelsa*, did better on this *robusta*-Quillou hybrid than on *excelsa*. To produce sufficient seeds of this *robusta*-Quillou hybrid, which was called Robusta 124.01, we had to use vegetative multiplication again in laying out fields for producing seed.

The small museum plots showed us also that the cropping time for the various clones was quite different; that among the high-yielders were early-cropping clones that gave their crop late in the season, and also some that gave berries with a long ripening-period. This was important from two points of view. If we could control the ripening-period and spread it over a larger number of months, we could improve the economy of our factory. On nearly all coffee plantations, drying capacity is the limiting factor, and is often insufficient to deal with the full crop during the peak-load, with the result that picking has to be slowed down, berries fall from the trees, and the berry borer may be encouraged. Control of this pest depends on having the trees for a certain period of the year free from berries of sufficient size to attract insects; it is obviously easier to use a fighting method based on this principle when all the trees synchronize in their cropping, than when trees with berries in various stages of growth compose the planting.

We also used grafting to raise hybrids. In the later years of our direction of the experiment garden we had to leave most of the work to the practical planter who managed it, and only occasionally could a botanist visit it. As we wished to obtain large quantities of hybrid seeds, and artificial pollination could not under the circumstances be carried out on a large scale, a set of grafts from several of our best clones was made, one of each species, and these grafts were planted out, well mixed, in a field called the 'Witch's Cauldron'. The seeds were laid out in nurseries, which were regularly inspected: if an apparently hybrid plant was found, it was marked, and as soon as the stem was large enough it was cut and used for making grafts on suckers of old, cut-back trees, as under these circumstances a graft produces nearly a year earlier than when it is made in the nursery and planted out. It is true that one cannot determine afterwards the species to which the father of the hybrid belongs, but this does not really matter; the only point of practical importance is whether the hybrid shows valuable characters, and this can only be found out by growing a small number of grafts.

After 1927 we had to give up this work for other occupations, but further developments have shown that some of the problems are more complicated than they originally seemed to be. Their solution is in the hands of an able man, and it may be that more time and more experimenting will be required than were at first anticipated. What we should study is not so much how we can apply vegetative multiplication to our tropical tree-crops, but how we can give it a larger place in our industry, and how we can make the best use of it to arrive at our ultimate goal of reducing production costs.

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A SIMPLE APPARATUS FOR MEASURING THE COMPACTNESS OF SOIL IN THE FIELD, AND SOME RESULTS OBTAINED IN A CULTIVATION EXPERIMENT

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WITH PLATES 4 AND 5

Introduction

WHEN agricultural field experiments involve treatments which cause differences in the physical condition of the soil, methods of assessing these differences in the field are needed. In this connexion the plough dynamometer [1] and the sieving method [2, 3] may be mentioned. Perhaps of even greater value are methods of measurement which can be applied when the crop is on the ground, so as to detect the persistence of the physical differences during the growing season and to give an estimate of the soil conditions in which the crop is actually growing. Apparatus suited to this purpose has been described by Keen and Cashen [4], and also by Balls at the Fifth International Botanical Conference, 1930. The principle in both these cases is that of a weight falling through a constant distance and driving a point into the soil, the amount of penetration with each impact being measured against a scale (Keen and Cashen) or automatically recorded on a tape (Balls). At any depth the distance of penetration per impact (Balls), or the number of impacts per unit distance of penetration (Keen and Cashen), gives a measure of the compactness of the soil at that depth.

Both the above-mentioned pieces of apparatus are rather costly and could only be made by a skilled apparatus-maker. The apparatus described below is a modification of them. In it the simple arrangement used for the falling weight resembles that described by Balls, but the amount of penetration is read off against a scale somewhat as in the apparatus of Keen and Cashen. It possesses the advantages of cheapness and ease of construction, and at the same time is thought to be sufficiently accurate in relation to the errors introduced by soil heterogeneity. Unfortunately, a direct test of the accuracy of the apparatus is not possible, since two sets of measurements obviously cannot be made in the same place, and owing to soil heterogeneity very different results may be obtained in a different place even when only a few inches away [4, p. 128]. Owing to this effect of soil heterogeneity it is necessary to make a number of sets of measurements for any one plot and to average the results. When this is done, errors such as might be due, for instance, to varying amounts of friction between the falling weight and rod may be expected to average out. It is shown below that the apparatus is capable of giving statistically significant differences between treatments in a cultivation experiment, even with as few as three sets of measurements per plot.

The cost of the complete apparatus was only a few shillings, the woodwork being carried out by the writer and the metal-work by a local

engineer. Since in these days the cost of a piece of apparatus is often the factor deciding whether or not it can be used, any reduction in cost that can be brought about without loss of efficiency is of importance.

Construction

The general arrangement of the apparatus is shown in Fig. 1 (Plate 4). A wooden tripod *T* supports an iron rod *R* bearing at its lower end a steel cone *C*. The length of steel pipe *P*, which surrounds the rod and rests on the upper end of the cone, serves to carry the force of the impact direct to the cone, the rod serving only as a guide. The weight *W* is lifted to a mark *M* and then allowed to fall freely, thus driving the point into the soil. The top of the tripod carries a wooden frame holding a cardboard mm. scale. After an initial adjustment of the zero by sliding the scale, the depth reached by the cone after each impact can be read off from the position of the top of the rod against the scale.

The following dimensions and constructional details have been found satisfactory. The triangular top of the tripod (5 in. sides) is made of $1\frac{3}{8}$ in. deal, drilled with a $\frac{1}{2}$ in. hole to take the rod. The legs, 5 ft. 3 in. long and made of deal of $\frac{13}{16}$ in. square section, are attached by single wooden screws on which they can pivot. This method of construction gives a very steady tripod. Details of the frame carrying the scale can be seen in Fig. 2 (Plate 4). It is 1 ft. 8 in. high, the piece of wood forming the back coming down only to within $1\frac{1}{4}$ in. of the tripod top. This leaves a space between the two side-pieces through which the surplus length of cardboard scale is drawn.

The iron rod, $\frac{3}{8}$ in. diameter and 6 ft. $2\frac{1}{2}$ in. long, is threaded at its lower end to screw into the cone. The latter is made of mild steel and is turned, drilled, and tapped, and then case-hardened. The original type of cone, which was used in obtaining the results described below, is shown in Fig. 3 (Plate 5). Its dimensions are: maximum diameter 2·3 cm., total length 6·1 cm., length of cylindrical upper portion 1·8 cm. An improved type of cone (Fig. 4, Plate 5) now being used has the following dimensions: diameter 2·3 cm., total length 5·1 cm., length of cylindrical upper portion 0·4 cm. Its upper part is recessed to a depth of 0·3 cm., the lower end of the pipe fitting into this recess. This ensures that the pipe remains concentric with the cone, and is therefore less likely to rub on the side of the hole in the soil. The shorter cylindrical portion is also an advantage, since it diminishes the total depth of soil on which the cone exerts friction at any one time, without greatly diminishing the total friction exerted by the cone. With the old type of cone the thread on the rod stripped after prolonged use, and it was thought that this might be due to the tube shifting to one side and transmitting some of the impact to the rod. This would be avoided with the new type of cone.

The pipe *P* is a piece of steel gas-pipe of outside diameter 1·6 cm. ($\frac{5}{8}$ in.) and length 45 cm. (1 ft. $5\frac{11}{16}$ in.). It is threaded at the top and fitted with a steel nut to strengthen it, and is further protected by a steel washer *S*. These precautions are necessary to prevent the upper end of the pipe from burring out. It will be noted that the outside diameter of

the pipe is less than the greatest diameter of the cone, so that the former should exert little or no friction on the sides of the hole in the soil. Were this not so an increasing length of pipe would exert friction as the cone was driven farther into the soil. The author has to thank Mr. G. H. Cashen for suggesting that the cone should be of greater diameter than the part above it.

The weight *W*, a cylindrical piece of iron, 7·5 cm. diameter, 2·2 cm. thick, and drilled in the centre with a 1·2 cm. ($\frac{1}{2}$ in.) hole, weighs 765 gm. (1 lb. 11 oz.). The distance from the mark *M* to the washer *S*, through which the weight falls, is 91·4 cm. (3 ft.). The energy of a single impact is therefore 69·9 kilogram-centimetres. Other weights and distances could, of course, be used to suit different soil conditions, but the above have been found to be generally suitable for the loam soil at Barberton.

The type of cone shown in Fig. 3 (Plate 5) integrates the resistance offered by the soil over a depth of 6·1 cm. In the absence of precise information as to the true weighted mean position in this distance of 6·1 cm., it is convenient to record depths as at the mid-point. Accordingly, another mark *m* is made on the rod, 103·05 cm. from the tip of the cone.

Method of Use

A 'soil-plate', such as that shown in Fig. 1, Plate 4 (S.P.), is placed flush with the general ground-level. The projecting tube of the plate serves to prevent loose surface-soil from falling into the hole. The plate figured was supplied with a soil-auger, but quite a serviceable one can be made of wood with a tin tube. The loose surface-soil in the tube is removed (generally to 3 or 4 cm. depth) and the apparatus set up. The tripod is adjusted so that the rod is parallel to a plumb-line and the scale parallel to the rod but not touching it. The initial depth of the mid-point of the cone below the soil surface is measured by the position of the mark *m* against a one-metre rule, held with one end standing on the soil-plate. The scale is adjusted to bring the reading at the top of the rod to this initial depth. This and the subsequent readings after each impact are written down. An assistant lifts the weight until the mark *M* is just visible below it, and then lets it fall. This is repeated as rapidly as the observer can write down the figures until the desired depth is reached. In moderately compact soil which is not very dry, determinations down to 35 cm. depth average about seven positions per hour, including the time taken to set up the apparatus. In very hard, dry soil such determinations may take half an hour for a single position.

Experimental

To illustrate the kind of data obtained with this apparatus, and the method of working them out, some actual results are given below. They were obtained on a cultivation experiment in which the three treatments were designed to give different degrees of soil compactness previous to planting. The cultural operations were carried out on the ploughed land early in November 1932, a caterpillar-tractor being used in all cases.

The three treatments, which were laid out in four randomized blocks, were as follows:

Normal. This treatment resembles the usual practice at the Cotton Experiment Station when moisture conditions are good, i.e. harrowing each way with a heavy peg-tooth harrow after spring rains, and a further harrowing one way with a light peg-tooth just before planting. This left the soil moderately compact but not excessively so.

Grubbed. This treatment consisted of a single harrowing by a heavy peg-tooth harrow crossed by a deep cultivation (to 9 in. depth) with a large rigid-tyne cultivator of the grubber type (Ransomes'). A further shallow cultivation was given with a spring-tyne cultivator just before planting. The soil was then extremely loose and soft right down to ploughing depth.

Compressed. The plots of this treatment had a heavy peg-tooth harrowing one way, crossed when the soil was not too moist by a tandem-disk harrow (set practically straight), a peg-tooth harrow, and a pulverizing roller. A further peg-tooth harrowing was given just before planting. This treatment left the land in a very compact condition.

The whole experimental area was planted with cotton on November 8, 1932.

Determinations of compactness were carried out on the cropped soil on December 21–2, after it had been beaten down considerably by heavy rains and hail (December 15–16). Each plot was divided transversely into three parts, determinations being made at one random position on each part. It would have been preferable to have two or more such sets of three positions for each plot, so as to obtain an estimate of the sampling error, but this was not possible.

For each separate position the field-readings were converted into 'number of impacts per cm. of penetration' for every cm. interval of depth from 9–10 cm. down to 34–5 cm. This was effected by plotting for each position the depth-readings against impact number. From this curve was read off the number of impacts for every successive cm. of penetration. A quicker method is to interpolate directly from the field-readings. The determinations above 9 cm. were not used, to make sure that the cone was completely buried in the soil. The compactness of the surface-soil was of little interest, having been affected by hoeing.

For every plot the mean 'impacts/cm.' for each cm. interval of depth was obtained from the values for the three positions. The treatment means obtained from these plot means are shown graphically in Fig. 5, in which the points are plotted in the centre of the 1 cm. depth-intervals. The curves present several features of interest. For each of the three treatments the compactness, as measured by number of impacts per cm., remains nearly constant from 9–10 cm. down to 17–18 cm. There follows a gradual increase down to 24–5 cm. (26–7 cm. for the 'Grubbed' treatment) and below this depth the number is again roughly constant. (The increase below 28–9 cm. in the 'Compressed' treatment is mainly due to one very hard plot and is almost certainly not significant.) It can be assumed that when the number begins to rise, at 18 cm., the tip of the

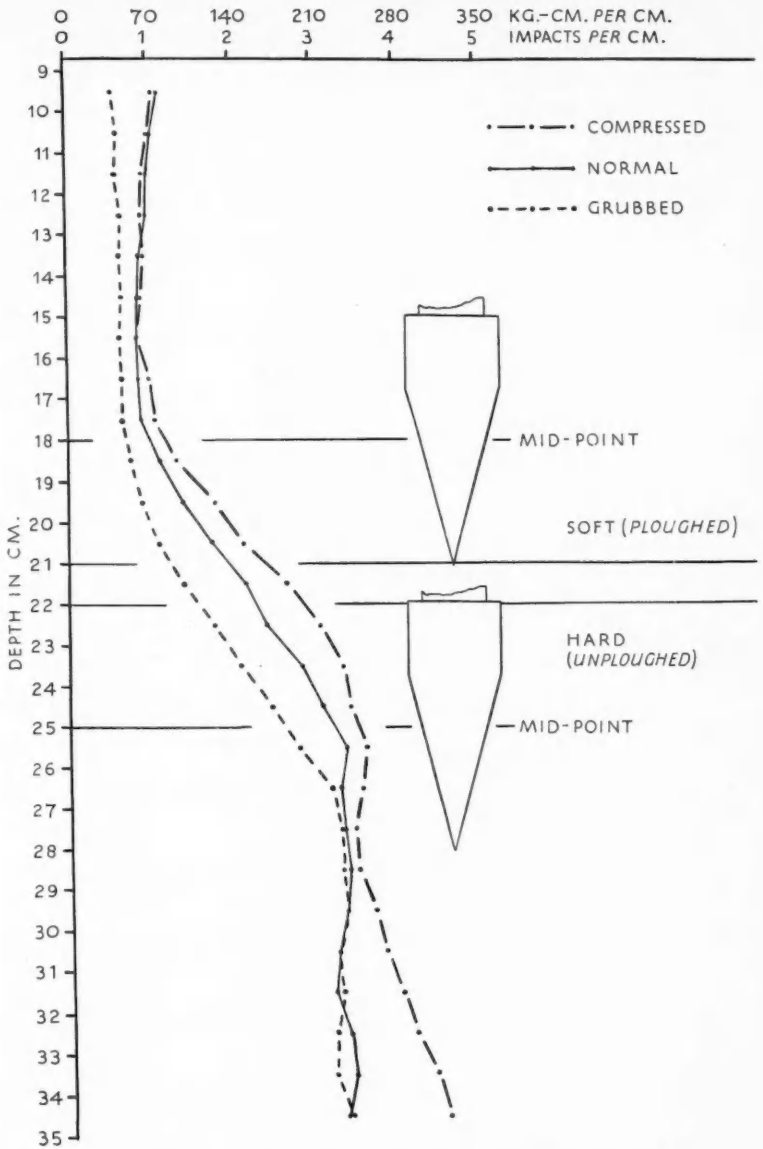

FIG. 5. Soil compactness, as measured by impacts per cm. of penetration. Treatment means.

cone (3·05 cm. below the mid-point) is just entering the hard soil at the bottom of the ploughing-depth, i.e. at 18+3 = 21 cm.; likewise that the gradual rise in number is due to more and more of the cone passing into the hard unploughed soil, and that the whole of the cone is buried in it when the number again becomes constant at 25 cm. (or 27 cm. for the 'Grubbed' treatment). Since there is 3·05 cm. of the cone above the point from which the depth is measured, this gives 25−3 = 22 cm. as the depth of the bottom of the ploughing (24 cm. for the 'Grubbed' plots). Thus the curves in Fig. 5 indicate a ploughing depth of 21–2 cm. Apparently the difference of 1 cm. between the two estimates is mainly due to the 'spread' caused by taking the mean of a number of positions; for an inspection of the impacts/cm. figures for individual positions shows that in most cases the number rises through a depth approximately equal to the length of the cone (mean 6·3 cm.) rather than through 7 cm., as in Fig. 5.

It has been mentioned above that after the gradual rise in number of impacts/cm. the number becomes roughly constant again at a depth approximately 2 cm. lower for the Grubbed treatment (Fig. 5). This implies that the bottom of the ploughing was about 2 cm. farther from the surface. Examination of the figures for individual positions confirmed this suggestion. For each separate position the beginning and end of the rise in number of impacts/cm. were determined by inspection, and the depth to the middle of this rise was taken to be the ploughing depth. The mean ploughing depth for each plot was obtained from the values for the three positions. The method of analysis of variance [5] applied to these plot means shows a significant effect of treatment on depth (z observed, 1·1018; z required for $P = 0{\cdot}05$, 0·8188). The treatment means are as follows: Compressed 21·30 cm., Normal 21·78 cm., Grubbed 23·33 cm. The significant difference between two treatment means is 1·22 for $P = 0{\cdot}05$ and 1·85 for $P = 0{\cdot}01$. The Grubbed treatment was therefore significantly deeper to bottom of ploughing than both Normal ($P < 0{\cdot}05$) and Compressed ($P < 0{\cdot}01$). Since the latter treatments were not significantly different their mean depth may be used, i.e. 21·54 cm. The depth for the Grubbed treatment was therefore 1·79 cm. greater than for the other two. It is probable that this was due partly to the grubber scratching up the bottom of the ploughing and partly to the extra volume occupied by the less compact grubbed soil.

The relative positions of the three curves in Fig. 5 indicate that the ploughed soil of the Grubbed plots was less compact than that of the Normal or the Compressed plots. Also that below the ploughing the Compressed plots were more compact than the other two treatments. The portions of the curves where the cone was partly in the ploughed soil and partly below seem to indicate that in the Compressed plots the soil at the bottom of the ploughing was slightly harder than in the Normal. These portions of the curves for the Grubbed and Normal treatments, however, cannot be said to indicate a difference at the bottom of the ploughing, if allowance is made for the greater depth of ploughed or grubbed soil on the former.

In order to test the validity of these indications the data have been

examined by analysis of variance. The plot means for 9–17 cm. depth (i.e. with the cone entirely in the ploughed soil) are shown in Table 1.

TABLE 1. *Mean Impacts/cm. in Ploughed Soil. Depth 9–17 cm.*

	I	*II*	*III*	*IV*	*Total*	*Mean*
Compressed	1·04	1·12	0·80	0·93	3·89	0·973
Normal	1·16	1·00	0·80	0·92	3·88	0·970
Grubbed	0·80	0·77	0·46	0·61	2·64	0·660
Total	3·00	2·89	2·06	2·46	10·41	

Analysis of variance applied to these figures gives an observed value of z for treatment effect of 1·9703, the value required for $P = 0{\cdot}01$ being 1·1955. Treatment effect was therefore highly significant. The significant difference between two treatment means is 0·087 for $P = 0{\cdot}05$ and 0·131 for $P = 0{\cdot}01$. The Grubbed treatment was therefore quite definitely less compact than either of the others ($P < 0{\cdot}01$).

The plot means for 27–35 cm. depth (i.e. with the cone entirely in the soil below the bottom of the ploughing) are shown in Table 2.

TABLE 2. *Mean Impacts/cm. Below Ploughing. Depth 27–35 cm.*

	I	*II*	*III*	*IV*	*Total*	*Mean*
Compressed	3·88	4·18	3·59	4·51	16·16	4·040
Normal	3·15	3·31	4·32	2·86	13·64	3·410
Grubbed	3·67	3·11	3·39	3·29	13·46	3·365
Total	10·70	10·60	11·30	10·66	43·26	

z observed for treatment effect, 0·3390. z required for $P = 0{\cdot}05$, 0·8188. The effect of treatment on the compactness below the ploughing was therefore entirely insignificant.

In order to test the significance of the differences in compactness at and near the bottom of the ploughing, analysis of variance was carried out on the plot means for 21·8–24·8 cm. depth for Grubbed but 20–3 cm. for the other two treatments, i.e. the Grubbed curve was effectively shifted up 1·8 cm. to make the bottom of the ploughed or grubbed soil coincide for all treatments.[1] The plot means are shown in Table 3.

TABLE 3. *Mean Impacts/cm. at and near Ploughing Depth, 20–23 cm. for Normal and Compressed, 21·8–24·8 cm. for Grubbed*

	I	*II*	*III*	*IV*	*Total*	*Mean*
Compressed	2·06	3·04	2·67	2·87	10·64	2·660
Normal	1·64	2·08	2·00	2·88	8·60	2·150
Grubbed	1·62	2·16	2·35	2·21	8·34	2·085
Total	5·32	7·28	7·02	7·96	27·58	

[1] Such an adjustment was not made in the data given in Tables 1 and 2. There is no evidence to show how much of the extra depth on the Grubbed plots was due to the grubber scratching up the unploughed soil, and how much to the extra volume of the grubbed soil. It is therefore impossible to say how far the Grubbed curve should be raised to make the same levels in the soil coincident for all treatments. In any case such a shift would not affect the conclusions reached from the data in Tables 1 and 2.

z observed for treatment effect, 0·8707. z required for $P = 0{\cdot}05$, 0·8188. The effect of treatment was therefore significant ($P<0{\cdot}05$). The significant difference between two treatment means is 0·456 for $P = 0{\cdot}05$ and 0·586 for $P = 0{\cdot}02$. Both the Normal and Grubbed treatments were therefore significantly less compact at and near ploughing depth than the Compressed treatment ($P<0{\cdot}05$). It is possible that before the hail and heavy rain had levelled out some of the differences between treatments, the ploughed soil of the Normal plots may have been less compact throughout its depth than that of the Compressed plots. On the other hand, it is likely that the compressing operations, carried out with the surface soil fairly dry, chiefly affected the wetter soil near the bottom of the ploughing.

Soil-moisture samples at 18–23 cm. and 23–30 cm. depth failed to show any significant difference between treatments. Inspection of the individual plot figures showed no very definite connexion between soil moisture and compactness. This may, however, have been due to the number of soil-moisture samples per plot being too small.

Conclusions. The measurements of compactness, made with the apparatus described, show that even after heavy rain and hail the ploughed soil of the Grubbed plots was very definitely softer than that of the Normal and Compressed plots; and that entirely below the bottom of the ploughing there was no difference in compactness between treatments. The only difference between the Normal and Compressed plots was in the compactness of the soil at and near ploughing depth. The depth to the bottom of the ploughed or grubbed soil was greater on the Grubbed plots than on the other two treatments.

Summary. The construction and method of use of an apparatus for measuring the compactness of soil in the field are described. It has the advantages of low cost and ease of construction, and is thought to be sufficiently accurate in relation to the errors introduced by soil heterogeneity.

Some results obtained with this apparatus on a cultivation experiment are discussed. Statistically significant differences between treatments were found, even with measurements in only three positions per plot.

I wish to thank Mr. F. R. Parnell for his kindly interest and helpful criticism. I am also very grateful to Dr. B. A. Keen and Mr. G. H. Cashen for describing their apparatus to me before publication.

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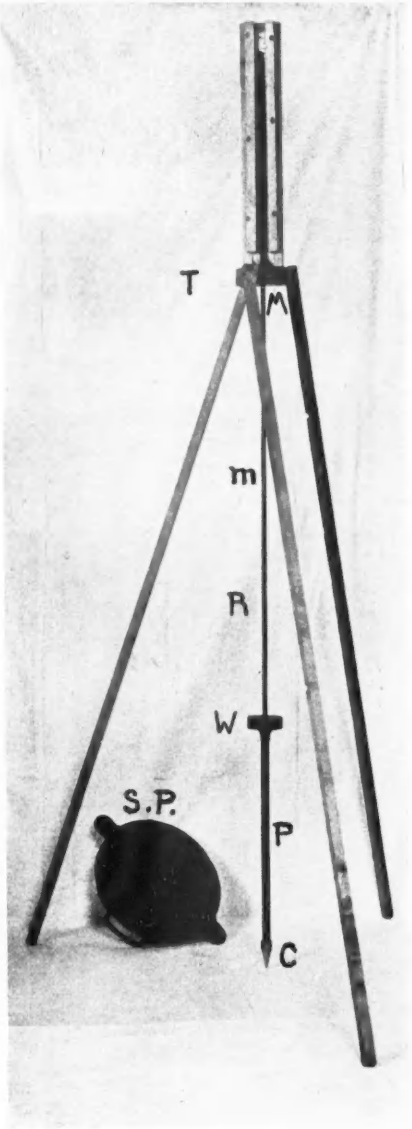

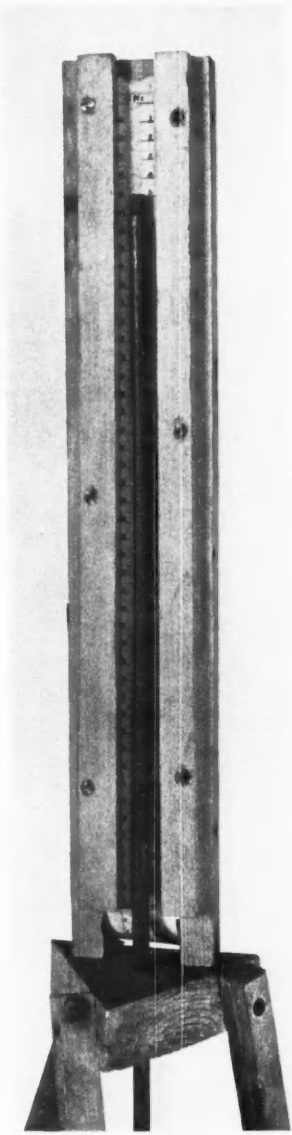

FIG. 1 FIG. 2

APPARATUS FOR MEASURING SOIL COMPACTNESS

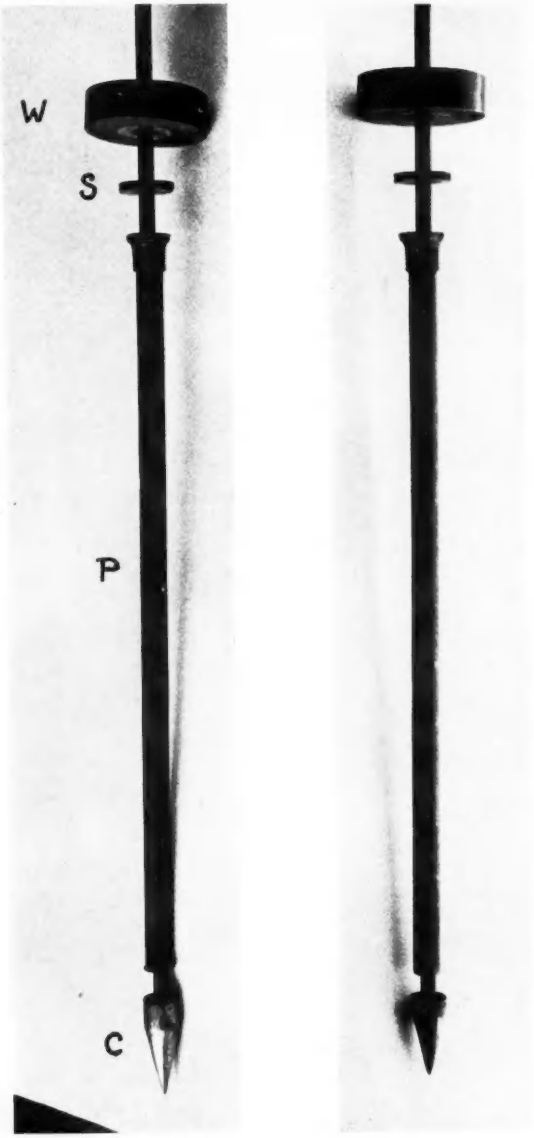

FIG. 3 FIG. 4

APPARATUS FOR MEASURING SOIL COMPACTNESS

THE CONTROL OF ANNUAL WEEDS IN CEREAL CROPS BY DILUTE SULPHURIC ACID

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THE first experiments on the destruction of weeds by chemical means were carried out during the last decade of the nineteenth century. The earlier work on copper compounds and ferrous sulphate has been summarized by Åslander [1] and Rabaté [2]. According to Rabaté, the use of dilute sulphuric acid to destroy weeds was first investigated by Bonnet, Brandin, and Duclos in 1898. These workers did not consider that the preliminary results they obtained by spraying cereal crops with 1·8–5·6 per cent. solutions warranted further trial.[1] After this investigation no further attention was paid to sulphuric acid until Rabaté took up the problem again in 1911. For many years Rabaté [3, 4, 5] carried out a large number of trials, mainly of an observational nature, on the destruction of weeds in cereal crops. He claimed that sulphuric acid was superior to other compounds, since by its use a larger number of species could be controlled, and successful results were less dependent on fine weather at the time of spraying. Weed species varied in their resistance to such treatment, the concentration of acid necessary for eradication ranging from 9·0 to 27·0 per cent., when 100 gallons of solution were applied per acre. Also, cereal crops differed in susceptibility to damage by sulphuric acid; winter wheat was the most resistant and spring-sown barley the most sensitive. Hitier [6] found that solutions of 3·0–7·0 per cent. gave the best results with spring-sown cereals. Loyer [7] sprayed spring oats with an 8·0 per cent. solution, whilst Jannin [8] successfully controlled weeds in flax with an 18·0 per cent. concentration. Garofalo [9] recommended strengths of 15·6–23·4 per cent. but, contrary to previous workers, claimed that the optimum time for spraying was at the 10–12 leaf stage of the cereal crops, and not at the usual 3–5 leaf stage. Experiments with sulphuric acid have also been carried out in America, where Brown and Streets [10] found that many weeds could be eradicated with strengths varying from 3·6 to 27·0 per cent. Muskett [11] has observed a decrease in weeds after spraying nurseries of seedling conifers with a 1·25 per cent. solution at the rate of 1 gallon per sq. yard. Gordon [12] claimed that *Pteris aquilina* is controlled by spraying twice with a 5·0 per cent. solution.

All the investigators so far cited have confined their attention to the actual eradication of weeds and have made little, if any, attempt to measure the increases in yield due to the elimination of competition from weeds. Korsmo [13] in Sweden has, however, carried out over 3,000 simple trials between 1916 and 1923 in which the yield was recorded. During the investigations Korsmo used solutions of various chemical

[1] All the concentrations of acid given in this paper are on a weight/volume basis. The majority of investigators worked on a volume/volume basis, since this would simplify the preparation of solutions in agricultural practice.

compounds, namely 15–25 per cent. ferrous sulphate, 6·4–9·2 per cent. sulphuric or nitric acid, also finely-ground calcium cyanamide, and 'charlock powder', a mixture of ferrous sulphate and gypsum in the proportion of 3 : 2. With the exception of 'charlock powder', which was inferior, all the treatments gave similar results, 73–82·5 per cent. of the weeds being killed. The relative effectiveness of the various treatments is reflected in the increases in yield obtained as a result of eliminating weed-competition in spring-sown cereals. Sulphuric and nitric acids, cyanamide and ferrous sulphate increased the yield on an average by 22·8–24·4 per cent., and 'charlock powder' by about 19 per cent.

In the present investigations attention has been confined to a number of the commoner weed species found in cereal crops, *Brassica sinapis* (Yellow Charlock), *Raphanus raphanistrum* (White Charlock or Runch), *Ranunculus arvensis* (Corn Buttercup), and *Papaver Rhoeas* (Field Poppy). In some of the trials copper sulphate was compared with sulphuric acid, in others only sulphuric acid at various concentrations was used. In each experiment, in addition to determining the yield of the crop, counts were made to measure both the degree of weed-infestation and the control obtained by the various spraying treatments.

Experimental Technique

Lay-out of plots.—Each experiment consisted either of random blocks or a Latin square. The size of plot varied from 1/80 to 1/100th acre, with 2–3 ft. paths between the plots.

Application of sulphuric acid solutions.—The dilute sulphuric acid was applied at the rate of 100 gallons per acre by means of a Vermorel Plombé Knapsack Sprayer.[1] Spraying was carried out when the weeds were still in the seedling stage, and the crop was seldom more than 6 inches high. In the experiments with copper sulphate the concentration used was 5·0 per cent., and the amount of solution applied was 100 gallons per acre.

Weed counts.—To determine both the degree of weed-infestation and the control obtained by the various treatments, counts were made of the number of plants found on each plot. The counts were carried out on all plots, including the controls, some three weeks after spraying, in order that plants which were only damaged by spraying might have time to recover. The estimate was obtained by throwing down at random 10–20 quadrats (1 ft. × 1 ft.) on each plot and noting the number of plants within the quadrat. The data obtained in this way are capable of statistical analysis according to the methods of Fisher [14].

Experimental Results

Control of Brassica sinapis

Experiments on the control of *B. sinapis* were carried out at the Station in 1932 and 1933. Since it was known prior to the spring of 1933 that none of the arable land available contained *B. sinapis*, it was

[1] A general account of tests with spraying machines for large-scale work is given by R. K. MacDowall in a pamphlet entitled 'Weed Destruction by Sulphuric Acid Spraying'. Oxford University Press, 1933.

decided to sow the seed of this species at the same time that the spring oats were drilled in. Germination-tests on seed from several sources showed that the germinative capacity of seed saved from the previous season was surprisingly low. In order to determine whether this low germination was due to a large proportion of 'hard' seeds, the seed was placed in concentrated sulphuric acid for various lengths of time. After this treatment, the seeds were transferred to a large volume of water containing excess calcium carbonate. Finally the seeds were spread out, allowed to dry, and sown in pans within forty-eight hours. In Fig. 1 it is seen that the percentage germination is very markedly increased by this treatment, the optimum time of immersion in the acid being 5 minutes. The seed for the field trial was treated in this way, since before treatment the germination was less than 1 per cent.

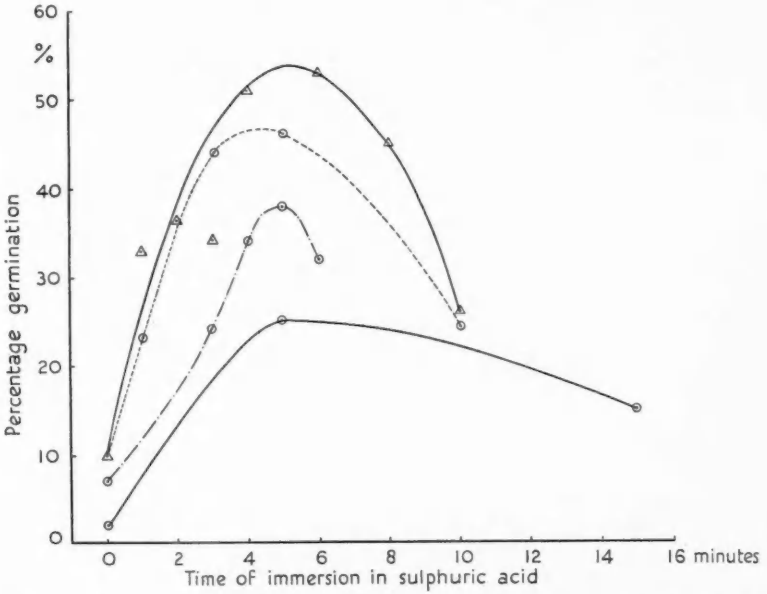

FIG. 1. Curves showing the increase in germinative capacity of *B. Sinapis* seed due to immersion in concentrated sulphuric acid for various lengths of time.

In both 1932 and 1933 sulphuric acid was compared with copper sulphate. The method of estimating the control obtained was somewhat different in each year. In 1932, in order to determine the amounts of minerals removed, the charlock from the various plots was hand-pulled some days prior to harvesting the cereal, and, after being dried, was weighed and analysed. The degree of control has therefore been expressed in terms of the weight of charlock harvested per plot. In 1933 this laborious method could not be undertaken, and counts of the number of plants per quadrat were made in the way already described.

The degree of control obtained in the two years is shown in Table 1. In 1932 copper sulphate was as effective as either 9·2 or 13·8 per cent. sulphuric acid. In 1933, however, whereas 9·2 per cent. sulphuric acid killed 96·8 per cent. of the charlock plants, the control obtained with copper sulphate was negligible. The disparity between the results with copper sulphate in the two years can be ascribed to differences in weather at the time of spraying. In 1932 spraying was carried out during a spell of fine dry weather; in 1933, three hours after spraying had been completed, heavy rain fell and washed the copper sulphate off the plants before it had penetrated the tissues. Sulphuric acid, owing to its very rapid action, was unaffected by the rain.

TABLE 1. *Brassica sinapis*

Percentage Control

	Treatments			*Sig. Diff.*
	Sulphuric acid		*Copper sulphate*	
Crop	*9·2%**	*13·8%**	*5·0%*	*(P = 0·05*
Oats 1932 (Victory)	94·0	96·1	98·2	24·9
Oats 1933 (Victory)	96·8	..	1·8	29·6

Yield of grain (cwt./acre)

	Degree of Weed infestation. Plants/ sq. ft.		*Treatments*					
			Sulphuric acid					
Crop		*Control*	*9·2% 100 g/acre*	*9·2% 60 g/acre*	*13·8% 100 g/acre*	*15·3% 60 g/acre*	*Copper sulphate 5·0%*	*Sig. Diff. (P = 0·05)*
Oats 1932 (Victory)	..	18·0	28·1	..	..	27·5	28·5	3·6
Oats 1933 (Victory)	8·4	13·04	20·04	20·0	20·98	..	..	7·13

* These concentrations correspond to 6·5 and 10·0 per cent. solutions of commercial B.O.V. on a volume-volume basis.

Relation between crop-yield and eradication of B. sinapis.—In both 1932 and 1933, experiments were carried out to determine the order of the increase in crop-yield obtained by eradicating *B. sinapis*. In 1932 the experiment was the same as that already described above. The treatments in 1933 consisted of 9·2 per cent. sulphuric acid applied at the rates of 100 and 60 gallons and 15·3 per cent. applied at 60 gallons per acre. The object of this experiment was to determine whether it was feasible to reduce the amounts of acid and water without diminishing the effectiveness of the weed control. It was found difficult to apply evenly with the knapsack sprayer the solution at the rate of 60 gallons per acre. Nevertheless, over a 90 per cent. 'kill' was obtained. The crop, however, was sprayed when the *B. sinapis* plants were small (4-leaf stage), and it is doubtful whether in a more advanced state, 60 gallons would suffice to wet efficiently the larger leaf-area. Further, unless the 15 per

cent. concentration was used, the actual amount of acid necessary to kill the tissues might be insufficient.

The yield data (Table 1) show that the eradication of *B. sinapis* by 9·2 per cent. sulphuric acid led in both years to an increase in yield over the control of 54–55 per cent. In 1932 similar increases occurred when the acid concentration was increased to 13·5 per cent. or when copper sulphate was substituted for sulphuric acid. As these treatments all gave equal control of *B. sinapis*, it would seem that though the oat crop appeared to be more damaged at the time of spraying by sulphuric acid, this damage had little, if any, effect on the final yield. In 1933 all the spraying treatments gave the same increases in yield.

Control of Raphanus raphanistrum

In 1933 four trials were carried out on the eradication of *R. raphanistrum*, and in each the yields were obtained as well as the degree of control. At two of the centres the crop consisted of spring oats growing on light soils of sandstone origin (Powderham and Milverton), whilst the two trials with spring barley were on Reading clay (Holyport) and an alluvial loam (Dorchester).

The results of the four trials are given in Table 2. In each experiment

TABLE 2. *Raphanus Raphanistrum*

Percentage Control

Centre	*Crop*	*Treatments*				*Sig. Diff.* ($P = 0{\cdot}05$)
		Sulphuric acid			*Copper sulphate* 5·0%	
		9·2%	13·8%	18·4%		
Powderham (Devon.)	Oats Victory	..	99·0	98·5	66·3	17·2
Milverton (Somerset)	Oats, White Abundance	57·4	89·8	96·3	..	17·3
Holyport (Berks.)	Barley Plumage-Archer	73·8	88·6	93·9	..	14·0
Dorchester (Oxon)	Barley Golden Archer	..	91·2	95·1	..	19·0

Yield of grain (cwt./acre)

Centre	*Degree of weed-infestation. Plants per sq. ft.*	*Treatments*					*Sig. Diff.* ($P = 0{\cdot}05$)
		Control	*Sulphuric acid*			*Copper sulphate* 5·0%	
			9·2%	13·8%	18·4%		
Powderham	4·8	22·13	..	23·38	19·45	23·08	2·48
Milverton	13·5	19·05	20·14	21·6	19·41	..	2·38
Holyport	18·5	22·59	22·62	22·89	21·93	..	2·72
Dorchester	24·0	10·52	..	18·36	18·92	..	1·67

spraying with a 13·8 per cent. solution of sulphuric acid led to an 88–99 per cent. destruction of *R. raphanistrum*. Increasing the concentration to 18·4 per cent. did not bring about a significantly greater degree of control. On the other hand, a reduction in concentration to 9·2 per cent. resulted in a significantly lower efficiency at both Holyport and Milverton. At Powderham 5·0 per cent. copper sulphate was not so effective as sulphuric acid. Spraying was carried out at Dorchester, Holyport, and Powderham during fine weather. At Milverton spraying was completed in light rain, and was followed by a period of dull weather. Differences in weather do not appear to have affected the degree of control obtained.

Relation between crop-yield and eradication of R. raphanistrum.—The control of *R. raphanistrum* by 13·8 per cent. sulphuric acid led to different results at the four centres (Table 2). In two of the trials significant increases in crop-yield were obtained by eliminating weed-competition, namely 13·4 per cent. at Milverton and 74·5 per cent. at Dorchester. At Powderham, where the infestation was slight and the crop backward and thin, control gave no increase in yield. That weed-competition was not one of the factors limiting the growth of the oats at this centre is suggested by the fact that spraying with copper sulphate, in spite of its ineffective control, led to the same yield as the treatment with 13·8 per cent. sulphuric acid. On the other hand, since the 18·4 per cent. concentration of sulphuric acid produced a significant decrease in yield, the 13·8 per cent. concentration may have damaged the crop more than the copper sulphate. At the other three centres, however, there was no significant depression in yield due to spraying with the higher concentration of acid.

At the two barley centres the disparity between the increases in yield obtained as a result of the elimination of *R. raphanistrum* cannot be explained by the difference in weed-infestation, as this was severe in both cases. A possible explanation will be given later.

Control of Ranunculus arvensis

Two experiments were made on winter wheat infested with *R. arvensis*. In both cases the soil was a heavy clay. Spraying was carried out during fine weather at a time when *R. arvensis* had formed either 4–5 leaves (Mortimer) or was in flower (Jealott's Hill). The measure of the control obtained is seen in Table 3. Treatment with 13·8–14·7 per cent. sulphuric acid led to an 83–96 per cent. 'kill'. At Mortimer, despite an increase of 50 per cent. in the concentration of the acid, the control obtained was no greater. Copper sulphate solution (5·0 per cent.) at Mortimer proved ineffective, but it was observed that the plants were 'checked' by spraying.

Relation between crop-yield and eradication of R. arvensis.—Only at one of the centres (Mortimer) was the yield of the crop recorded. Table 3 shows that the eradication of *R. arvensis* by sulphuric acid did not result in a significant increase in yield. Quite apart, however, from the question of weed-competition, the absence of the achenes of *R. arvensis* from the grain would improve the market value of the wheat. Wheat so con-

taminated cannot be sold for milling, and if the achenes are present, it is extremely difficult during threshing to obtain a clean sample of grain.

TABLE 3. *Ranunculus arvensis*

Percentage Control

Centre	Crop	Treatments: Sulphuric acid 13·8%	Sulphuric acid 14·7%	Sulphuric acid 22·1%	Copper sulphate 5·0%	Sig. Diff. ($P = 0.05$)
Mortimer (Berks.)	Winter wheat (Red Standard)	..	83·4	91·4	15·1	28·1
Jealott's Hill, Berks.	Winter wheat (Chevalier)	96·2	..	..	..	30·4

Crop Yield (cwt./acre)

Centre	Degree of weed-infestation. Plants per sq. ft.	Treatments: Control	Sulphuric acid 14·7%	Sulphuric acid 22·1%	Copper sulphate 5·0%	Sig. Diff. ($P = 0.05$)
Mortimer	16·0	17·91	20·51	20·82	20·42	4·65

Control of Papaver Rhoeas

Two trials were laid down in 1933 on the control of *P. Rhoeas* growing in winter wheat. In both cases the crop was thin at the time of spraying. At one centre (Brough) the very light sandy soil could not be considered ideal for wheat-growing.

Since the work of Rabaté [2] indicated that poppies were more resistant to sulphuric acid than many other species, spraying was carried out with concentrations of acid considerably higher than those previously used. At one centre (Medmenham), however, a 9·2 per cent. concentration was included, as, in addition to *P. Rhoeas*, *Galium aparine* was also present in the crop. The degree of control obtained is seen in Table 4. At Brough the results of spraying *P. Rhoeas* were more successful; solutions of 18·4 and 23·0 per cent. gave a significantly greater degree of control than one of 13·8 per cent. strength. At Medmenham, spraying with a 27·6 per cent. concentration was less effective than 13·8 per cent. acid at Brough. This discrepancy between the two centres cannot be attributed to differences in weather, since in both trials the weather was hot and sunny at the time of spraying. These differences in susceptibility may, however, have been due to the more advanced stage of growth of *P. Rhoeas* at Medmenham. This supposition is contrary to the claims of Rabaté, who states that the most effective 'kill' can be obtained when the first flower-head is forming.

All the treatments with sulphuric acid gave more or less complete control of *G. aparine*. This species can therefore be classed with *B. sinapis* as being particularly susceptible to spraying with sulphuric acid.

TABLE 4. *Papaver Rhoeas*

Percentage Control

Centre	Crop	Treatments: Sulphuric acid 9·2%	13·8%	18·4%	23·0%	27·6%	Sig. Diff. ($P = 0·05$)
Brough (Yorks.)	Wheat (Little Joss)	..	63·0	72·4	78·4	..	9·1
Medmenham (Bucks)	Wheat (Garton's Renown)	22·4	..	30·9	..	60·3	46·9
Galium aparine:							
Medmenham		99·7	..	99·3	..	100·0	28·8

Yield of crop (cwt./acre)

Centre	Degree of weed-infestation. Plants per sq. ft.	Control	Treatments: Sulphuric acid 9·2%	13·8%	18·4%	23·0%	27·6%	Sig. Diff. ($P = 0·05$)
Brough	29·4	8·15	..	8·71	9·10	9·10	..	1·12
Medmenham	15·0 P.R. * 7·7 G.A.	5·03	5·85	..	5·59	..	6·11	0·87

* P.R. = *P. Rhoeas*. G.A. = *G. aparine*.

Relationship between crop-yields and eradication of Papaver Rhoeas.—In both these trials the yield of grain was far below normal. At Brough, in spite of a high degree of weed-infestation and a 78·4 per cent. control, there was no significant increase in yield. At Medmenham, where there were only half as many poppies present as at Brough, spraying with 27·6 per cent. acid led to only a 60·3 per cent. control, but an increase in yield of 21 per cent. This difference at the two centres might be ascribed to the elimination of both *P. Rhoeas* and *G. aparine* at Medmenham, but if this was so, then the 9·2 per cent. and 18·4 per cent. concentrations, both of which eliminated *G. aparine only*, should also have brought about significant increases in yield.

Susceptibility of Barley to Damage by Sulphuric Acid

The evidence of the French workers [2, 6] indicated that among cereal crops spring barley was most liable to be damaged by spraying with sulphuric acid. Experiments were undertaken at Jealott's Hill in 1932–3 to determine if this damage affected the yield of grain. In 1932 two similar experiments were carried out on a heavy-tillering Swedish variety, 'Opal'. As it was considered that the time of spraying might be of greater importance than the strength of the acid used, the crop was sprayed with a 9·2 per cent. concentration of acid when the third, sixth, and ninth leaf had fully developed. In 1933 a trial was carried out with 'Spratt-Archer'; and in addition to the treatments of the 1932 experiments, two further strengths of acid (13·8 per cent. and 18·4 per cent.) were applied at the three-leaf stage.

The results of the two years' experiments are given in Table 5. It is seen that a significant depression in yield resulted from spraying both Spratt-Archer and Opal at the later stages of growth, the order of the depression being greater for Opal. The data for the third-leaf stage again suggest that Opal is more liable to damage by spraying, although the depressions in yield were not actually significant in both the 1932 experiments. No decrease in yield occurred with Spratt-Archer even after treatment with an 18·4 per cent. solution at the third leaf stage.

TABLE 5. *Yield of Barley (cwt./acre)*

			Treatments					
			Stage of growth					
			3rd leaf			*6th leaf*	*9th leaf*	*Sig. diff.*
	Experiment	*Control*	9·2%	13·8%	18·4%	9·2%	9·2% H_2SO_4	($P = 0·05$)
1932	Opal (i)	29·61	24·98	..	..	18·51	25·29	5·3
	(ii)	28·53	21·65	..	..	19·79	20·46	7·76
1933	Spratt-Archer	25·85	24·89	27·46	29·78	21·09	19·15	4·59

Influence of Sulphuric Acid on Malting Quality of Barley

As it was not known what effect spraying with sulphuric acid had on the malting quality of barley, samples of the grain from the three barley trials made in 1933 were submitted for valuation in the London market. To obtain further information on the quality of the grain, the nitrogen-content and the 1,000-corn weight were also determined. From these data the amount of extract in brewers' pounds per quarter of dry malt was calculated on the basis of Bishop's formula [15].[1] The percentage germination was also determined.

The data given in Table 6 show that neither the germination nor the malting quality of the grain was materially affected by spraying with sulphuric acid. At Holyport, spraying at the third-leaf stage with solutions varying from 9·2 to 18·4 per cent. produced no appreciable change in grain-weight, nitrogen-content, or malting quality as determined either by Bishop's formula or by the market price. Again, at Dorchester the malting quality was not affected by such treatment. There are, however, indications that the nitrogen-content was increased, but was offset by a significant increase in grain-weight as a result of spraying. At Jealott's Hill, spraying at the later stages of growth led to a reduction in grain-weight. It would also appear that spraying tended to raise the nitrogen-content of the grain, irrespective of the strength of acid or the time of application. These changes, however, were not great enough to affect the malting quality.

Discussion

These experiments have shown that by means of sulphuric acid it is possible to control a number of the commoner annual weeds growing

[1] $E = K - 10·5\,N + 0·2\,G \pm 1·4$. Where E = brewers' extract, K = a constant dependent on the variety of barley, N = nitrogen-content, and G = 1,000-corn weight.

TABLE 6. *Effect of Spraying with Sulphuric Acid on the Malting Quality of Barley*

Centre	*Treatment*	*Percentage germination*	*1,000-corn weight. (gm.)*	*Nitrogen content %*	*Brewers' extract lb/qr. of malt*	*Market valuation (Dec. 1933). Shillings per quarter*
Holyport: (Plumage Archer)	Control	86	39·4 ±0·3	1·41	101·4	45
	3rd leaf 9·2% H_2SO_4	82	39·15±0·25	1·48	100·6	43
	3rd leaf 13·8% ,,	88	38·6 ±0·15	1·46	100·7	44
	3rd leaf 18·4% ,,	87	39·1 ±0·25	1·41	101·3	43
Dorchester: (Golden Archer)	Control	99	36·7 ±0·35	1·30	101·7	43
	3rd leaf 13·8% H_2SO_4	99	42·4 ±0·45	1·43	101·5	44
	3rd leaf 18·4% ,,	97	40·9 ±0·30	1·43	101·2	42
Jealott's Hill: (Spratt-Archer)	Control	98	44·35±0·45	1·34	103·4	38
	3rd leaf 9·2% H_2SO_4	96	41·95±0·4	1·41	102·2	36
	3rd leaf 13·8% ,,	97	43·0 ±0·6	1·41	102·4	37
	3rd leaf 18·4% ,,	97	43·2 ±0·3	1·46	101·9	36
	6th leaf 9·2% ,,	97	39·2 ±0·6	1·43	101·4	37
	9th leaf 9·2% ,,	97	38·75±0·73	1·37	102·0	38

in cereal crops. The concentrations found necessary to eradicate the various weed species are not entirely in agreement with the findings of previous workers. Rabaté claimed that *P. Rhoeas* was controlled by solutions of 18·4–25·8 per cent., whilst Korsmo [13] stated that solutions of 6·4–9·2 per cent. were effective. In the present investigations complete control was not obtained with solutions as high as 27·6 per cent., and solutions of 9·2 per cent. proved quite ineffective. For the eradication of *B. sinapis*, *R. arvensis*, and *R. raphanistrum*, the concentrations used were similar to those recommended by Rabaté. Korsmo, however, stated that both *R. raphanistrum* and *G. aparine* were controlled by strengths of 6·4–9·2 per cent. In the trials under review there is confirmation in the case of *G. aparine*, but the experiments at Milverton and Holyport showed that a 9·2 per cent. solution did not successfully control *R. raphanistrum*.

Aslander [16] investigated the action of sulphuric acid on the leaf-tissues and the resistance of various species to damage by spraying. The actual penetration of the acid took place first through the stomata, and more slowly through the epidermis. He found that dilute solutions attacked most readily the mesophyll tissue; killing the protoplasm and disorganizing the chloroplasts. In addition, the acid combined with the chlorophyll to form magnesium sulphate and phaeophytin.

Aslander found that the amount of damage was proportional to the quantity of acid adhering to the leaves. He confirmed the conclusions of earlier workers, viz. that differences in susceptibility to damage between species are in part attributable to their growth-form. Weeds such as *B. sinapis* would receive more acid on the horizontal surfaces of their leaves than the cereals with their upright habit of growth. In addition, the cereal crops have a further advantage; the growing-point is protected by leaf-sheaths, and a layer of cutin prevents, to some extent, the adher-

ence of the spray to the leaf. Åslander showed that the cutin on the under surface of the leaf was less protective than that on the upper. He considered that the damage due to sulphuric acid was proportional to the area of the lower surfaces sprayed. As the crop became more mature, the liability to damage would increase on account of the greater area of the lower surfaces exposed to the spray. This conclusion is in agreement with the data for barley (Table 5).

Apart, however, from morphological differences, resistance to damage by sulphuric acid was dependent on the rate of growth. Åslander [24] showed that plants of *B. sinapis*, grown either in the field during winter or in pots where the growth was limited by inadequate water supply, required a greater strength of sulphuric acid to kill the leaves than plants grown in abundant moisture. He attributed this greater resistance of the slow-growing plants to the compact structure of the leaf with its well-developed palisade-tissue and a thickened epidermis.

Åslander [1] suggested that differences in the rate of growth of weed species probably accounted for the discrepancies in the strengths of acid recommended by Rabaté and Korsmo. He pointed out that the majority of Rabaté's results were obtained on weeds growing in winter wheat, whilst Korsmo's investigations were confined to spring-sown cereals. Although his explanation might hold in the case of these workers, the higher concentrations found necessary to eradicate *R. raphanistrum* in England cannot be explained on this assumption, as both in the present investigation and in Norway the spraying trials were carried out on spring cereals. As an alternative hypothesis, it would appear necessary to postulate that the greater resistance of *R. raphanistrum* under English conditions must be due to morphological differences in the leaf and stem.

Information on the relative susceptibility of cereal crops to sulphuric acid solutions is also forthcoming from these trials. Wheat would appear to be the most resistant. Varieties such as Red Standard, Little Joss, and Renown were not affected by 22–23 per cent. concentrations. Spring oats (Victory) were undamaged by an 18·4 per cent. solution, but at Powderham a depression in yield resulted from spraying a thin crop of 'White Abundance' with acid of this strength. In the case of barley, experiments have shown that varieties would appear to differ in their resistance. Opal was injured in the young stages by a 9·2 per cent. strength, while Spratt-Archer was unaffected by even an 18·4 per cent. solution. Spraying at the later stages of growth produced a depression in both varieties. The evidence from the Dorchester trial suggests that when sprayed in the earlier stage of growth, Golden Archer is unaffected by an 18·4 per cent. solution.

These investigations have shown that the presence of a weed species in considerable quantity does not necessarily lead to a poor yield of the cereal crop. It has been seen in the Mortimer experiment that the competition from 16·0 plants per sq. ft. of *R. arvensis* did not prevent a normal crop of wheat being grown (17·91 cwt. per acre). Again, at Holyport, where there were 18·5 plants per sq. ft. of *R. raphanistrum*, a yield of 22·59 cwt. per acre of barley was obtained. It might be argued that

both these species could not compete successfully with the crop. On the other hand, the presence of *R. raphanistrum* at Dorchester (24·0 plants per sq. ft.) lowered the yield of barley to 10·52 cwt. per acre, and the control of this species by spraying increased the yield by 75 per cent. As in the two trials on barley infested with *R. raphanistrum*, there is similar disagreement in the two experiments on winter wheat infested with *P. Rhoeas*. At one centre (Medmenham) a 60·3 per cent. control resulted in an increase in yield of 21 per cent.; at the other (Brough), where the degree of infestation was nearly twice as great (29·4 plants as against 15·0 plants per sq. ft.), eradication of 78·4 per cent. of the weeds led to no increase.

Before any attempt can be made to explain the variable effect of the weed-population on the crop, it is necessary to consider the likely factors controlling competition. In spring-sown cereals, germination of the weed-seeds occurs at the same time as that of the grain, but maturity is reached much in advance of the cereal. Competition, therefore, is greatest in the earlier stages of growth of the crop. On *a priori* grounds, it would be expected that this competition would be primarily for the soil nutrients, water, light, and air.

In the Jealott's Hill experiment of 1932, when the mature plants of *B. sinapis* were hand-pulled, it was found that the total production of dry matter was only about 9·4 cwt. per acre.[1] The amounts of nitrogen, phosphates (P_2O_5), and potash (K_2O) removed per acre in the *B. sinapis* crop were 7·8, 5·8, and 10·5 lb., respectively. Other experiments at this Station have shown that cereal crops do not on this soil respond to applications either of phosphates or of potash. It seems therefore unlikely that the removal of this small quantity of nitrogen could to any great extent have governed the very marked depression in yield of oats brought about by the weed population.

Although no detailed study was made of the root systems, the conclusion was reached that *B. sinapis* and *R. raphanistrum* had shallower roots than either barley or oats. It would therefore be expected that the shallower-rooted weed species would be more susceptible to drought. This conclusion was to some extent confirmed by observation. It was noticed on several occasions in 1933 that at a time when these weed species were in a wilted condition, there was no sign of water shortage in the crop.

The above observations suggest that competition between the weed species and the cereal crop is in the main for light and air. Under conditions favourable to the weed species, such as wet weather, the 'smothering' effect of the weed would be severe. Under unfavourable conditions, such as drought, a slow growth-rate of even a large number of plants might have little effect on the crop. Again, this difference in the competitive power of the weed species would also be related to the rate of growth of the cereal. In a dry year, relatively to the weed species, the

[1] It is interesting to note that the number of seeds of *B. sinapis* obtained represented a sowing of sixteen million seeds per acre, or 370 seeds per sq. ft. In 1933 the destruction at Jealott's Hill of 8·4 plants of *B. sinapis* per sq. ft. led to an increase in yield of 54 per cent.

growth of the drought-resistant cereal would be more rapid than in a wet year.

If weed-competition is primarily a smothering effect, dependent to a large extent on an adequate supply of moisture, then the discordant results obtained at Holyport and Dorchester might be ascribed to differences in the available moisture-supply during the earlier stages of growth. As in both experiments *R. raphanistrum* germinated in the latter half of April and reached the flowering stage before the end of June, it would be expected that the greatest smothering effect would occur during May. Differences in rainfall during this month should therefore, on the hypothesis put forward, determine to a great extent the intensity of competition. The rainfall at the two centres would appear to confirm this contention. In April the rainfall was very similar (1·12 in. as against 1·17) but in May Dorchester received 3·04 in. and Holyport only 1·82 in. In the first half of June there was again little difference in rainfall at the two centres (0·2 in. at Holyport and 0·0 in. at Dorchester). No account has been taken of possible differences in the rate of evaporation at the two centres, but the figures for hours of sunshine (Oxford and Jealott's Hill) suggest that evaporation was greater at Holyport. In addition, although no determinations were made, the topography of the experimental sites suggested that the water-table was nearer the surface at Dorchester than at Holyport.

Rabaté considered that apart from the elimination of weed-competition, the increases in yield obtained from spraying with sulphuric acid were also in part due to increased nitrification. Braun [17], on the other hand, could not detect any increase in the supply of available nitrogen, phosphates, and potash after spraying, whilst Bowser and Newton [18] found that sulphuric acid tended to depress both the number of soil microflora and the rate of nitrification. On light soils deficient in calcium, spraying might depress nitrification by increasing the hydrogen-ion concentration of the soil. Brioux [19] showed that the depression in such soils might be from pH 6·4 to pH 5·6, but in calcareous or neutral soils spraying resulted in a temporary change of pH lasting at the most a few days.

The trials under review give little support to Rabaté's contention. If sulphuric acid brought about a marked increase in nitrification, then it would be expected that the spraying of weed-free crops would lead to an increase in yield. Such increases were not obtained in the barley trials. It might, however, be argued that the possible stimulus due to increased nitrification was counterbalanced by the injury to the crop. The other experiments do not support this hypothesis, since the increases in yield obtained were correlated with the eradication of the weed species, and showed no relation to the amount of acid applied.

Summary

Replicated experiments were carried out in 1932–3 at eight centres to determine the efficiency of dilute sulphuric acid for destroying annual weeds in cereal crops. Counts of the weeds were made to estimate the degree of control, and the plots were harvested to determine yields. All solutions were applied from a knapsack sprayer at the rate of 100 gallons

per acre. The weeds were sprayed as a rule in the seedling stage. The chief results obtained were:

Weed Control. Spraying in fine weather either with 9·2 per cent. sulphuric acid (9·2 gm. H_2SO_4 per 100 c.c.) or with 5·0 per cent. copper sulphate gave a 94·0–98·0 per cent. control of *Brassica sinapis*. On one occasion when rain fell within three hours of spraying, 5·0 per cent. copper sulphate solution was ineffective, while 9·2 per cent. sulphuric acid destroyed 96·8 per cent. of the plants. *Galium aparine* was eradicated by 9·2 per cent. sulphuric acid. Sulphuric acid of 13·6–18·4 per cent. concentration destroyed over 90 per cent. of the plants of either *Raphanus raphanistrum* or *Ranunculus arvensis*; 5·0 per cent. copper sulphate was less effective than the sulphuric acid solutions. *Papaver Rhoeas* was more resistant to sulphuric acid than the other weeds. At one centre spraying with a 23·0 per cent. solution reduced the weed-population by 78 per cent., but in another trial a 27·6 per cent. concentration gave only a 60 per cent. control.

Effect on yield. The eradication of *B. sinapis* in spring oats by either sulphuric acid or copper sulphate led at one centre to an increase in grain of 54–6 per cent. in both 1932 and 1933. At one centre an increase of 13·4 per cent. in the yield of spring oats was obtained by the eradication of *R. raphanistrum*. In a similar trial, where the weeds were less dense, no increase resulted from control. In two barley trials, destruction of *R. raphanistrum* was followed by a 75 per cent. increase in yield at one centre and none at the other. Partial control of *P. Rhoeas* (60–78 per cent.) in winter wheat did not affect the yield at one centre, but gave a 21 per cent. increase at another. Eradication of *R. arvensis* from winter wheat did not result in an increased yield.

Damage to crop. A 9·2 per cent. solution of sulphuric acid diminished the yield of both Opal and Spratt-Archer barley when applied at the later stages of growth; in the 'third-leaf' stage Spratt-Archer appeared to be more resistant than Opal. At this stage no damage was caused to Spratt-Archer by acid of 18·4 per cent. concentration. Spraying with sulphuric acid solutions did not affect the malting quality of the barley.

Nature of competition. It is concluded that the depressing effect of weeds is due primarily to shading and not to depletion of the supply of available nutrients in the soil. Competition is governed (i) by the density of the weed-population, and (ii) by the relative growth-rates of crop and weeds. Under conditions favourable to the weeds, e.g. wet weather, the more rapidly maturing weeds may smother the crop; under unfavourable conditions, e.g. a dry season, the more drought-resistant cereal crop may 'grow away' from the weed. It is considered that the differences in the competitive power of *R. raphanistrum* in the two barley trials can be ascribed to differences in rainfall.

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PASTURE LEGUMES IN RELATION TO GRASSLAND IMPROVEMENT IN AUSTRALIA

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IT is becoming increasingly evident that pastures are not at their best and do not form a properly balanced ration for stock unless legumes form an integral part of them. In most lowland districts of Britain clovers will make an unsown appearance on pastures if certain edicts connected with manuring and pasture management have been followed. Britain possesses vast areas of rough grazings or 'natural pastures', as they would be termed in Australia, which are characteristically non-leguminous, and the first precepts in any scheme of improvement entail the introduction and successful maintenance of clovers and other suitable legumes. The problem of improving our mountain pastures in Wales is closely akin to the parallel problem of improving natural pasture in Australia, for in the unimproved state both grassland types are markedly deficient in clovers. The problems they each present to the grassland improver are remarkably similar, although in one case they are associated with a cold, humid climate and in the other with a hot, dry climate.

The indigenous vegetation of Australia is rich in shrubby and tree forms of the Leguminosae, but is extraordinarily poor in herbaceous legumes. In the search for suitable pasture legumes, Australia has therefore to rely upon introductions from other parts of the world.

Australia (including Tasmania) lies between the latitudes 44° S. and 11° S. The continent is divisible into two major latitudinal zones, viz. a temperate belt in the south, and a sub-tropical and tropical belt to the north. The climate of both zones is marked by intense periodic drought. In the temperate zone there is winter rainfall with summer drought accompanied by high summer temperatures. In the sub-tropical and tropical zone the rainfall, although on the average greater in amount, is markedly more erratic in distribution and the dry period occurs characteristically in the winter.

In the southern temperate zone the paucity of indigenous pasture legumes has been largely made good in the agricultural areas by the host of temperate exotic legumes that has invaded the grasslands, especially by annual species of the genera *Trifolium* and *Medicago*, which are largely of Mediterranean origin, but have now become quasi-indigenous in the temperate grasslands of Australia. In many regions of high rainfall in southern Australia, our British perennial clovers also find a suitable habitat. Broadly speaking, therefore, the search for suitable species of clovers and other legumes does not now present an important problem in these districts, and efforts are being transferred to the improvement of strains within existing species of recognized value.

The sub-tropical and tropical zone is, however, less fortunately situated; and pasture development, both in terms of maintenance and improvement, is closely associated with the problem of finding suitable

species of legumes. What is wanted in this zone is a clover-like plant, self-regenerating and aggressive, which is of immediate grazing value and can be incorporated quickly and cheaply into the existing swards. This is precisely what has been accomplished in temperate parts of Australia by the introduction of exotic annual legumes, where, in presence of adequate dressings of phosphate, subterranean clover has transformed whole tracts of grazing land that were originally suitable only for store sheep and wool-growing into fattening and dairy pastures. Further, the vigorous growth of clover, together with the increased stock-carrying capacity of the land, has markedly improved the fertility of the soil. This improvement in soil fertility has made possible the complete transformation of the original sward, which consisted of grasses tolerating low fertility, into one in which perennial grasses demanding high fertility take a dominant place. Concurrently with these improvements, the extensive system of grassland farming is being replaced by more or less intensive methods, and as a result the large paddocks of the ranches are gradually being subdivided into smaller fields.

The important problem of pasture improvement in tropical and sub-tropical Australia, both in areas of natural steppe as well as on the biotically induced grasslands (i.e. de-forested and other areas maintained in grass under biotic influences), hinges very largely upon finding suitable legumes. Successful growth of legumes provides a ready and economic method of building up soil fertility, particularly with reference to the increase of organic material in the soils.

The importance of increasing the reserves of organic material in tropical soils has been stressed by Howard and Wad [1], who have recommended composting under certain conditions in India. Vageler [2] also has emphasized the deficiency of humus in tropical and sub-tropical soils that is caused by the extremely rapid decomposition of organic matter. This is an important point, and the condition is reflected in the light colour of most tropical soils in contrast with the much darker hue of soils in temperate zones. It is obvious that means have to be evolved to replenish the organic reserves in tropical soils. Composting on the Indian system could not be carried on extensively in Australia, and, as a system, would hardly be practicable except in densely populated countries where intensive husbandry is the rule. In the sparsely populated areas of the Australian tropics and sub-tropics only extensive methods are applicable at present. The key to pasture improvement in these areas is the solution of the legume problem.

By their capacity to make use of atmospheric nitrogen, legumes add materially to the reserves of nitrogen-rich organic compounds in the soil. They are upbuilders of soil fertility in a direct sense and help greatly to make edaphic conditions conducive to the growth of the more valuable perennial grasses that require a reasonably high standard of soil fertility. Furthermore, most of our pasture legumes are themselves rich in minerals and protein. Animal diseases associated with herbage deficient in minerals seldom occur on clover-rich pastures.[1] With very

[1] The 'wasting' disease (acute osteomalacia) prevalent among dairy cattle in the Denmark district of Western Australia appears to contradict this statement. In this

few exceptions the recorded instances of disease in stock due to mineral deficiency, both in tropical and temperate regions, occur on grasslands that are typically non-leguminous. In Britain, these diseases are largely confined to our clover-deficient mountain grazings. When the pastures have been so improved that they carry a body of clovers, the visual symptoms of disease become rarer and the general health of the stock is improved. The same may be said of most areas in Australia where mineral-deficiency diseases have occurred in stock grazing on unimproved pastures [7].

Where deficiency diseases occur in the extensive pastoral districts, and where more intensive methods cannot be immediately applied, stock-licks, rich in the appropriate minerals and in protein, have been used successfully as correctives to provide the ingredients in which the herbage is deficient. By this means the animals have been maintained in better health, and losses have been minimized. Licks will always be valuable as supplementary sources of mineral and other foods even on improved pastures, but they should be regarded only as supplements or as temporary palliatives, and not as an alternative to pasture improvement.

Experience of rough grazings in Wales during the past two decades has indicated that there should be two phases in the improvement of these poor legume-deficient pastures, viz. (1) the maintenance of clover as the dominant element in the sward for a number of seasons in order to improve soil conditions, and (2) the subsequent introduction of improved forms of grasses. The mixture of grass and clover provides a more balanced diet, is more productive, and has a longer season of growth than pure clover or even dominant clover. Australian experience generally would serve to corroborate in principle the dual nature of the pasture-improvement problem. In southern districts of Australia subterranean clover, given appropriate conditions (phosphates are always essential), will assume complete dominance in the pastures. There are hundreds of thousands of acres in temperate Australia which are now in the phase of dominance by subterranean clover. The next step in improvement is to incorporate into them grasses, such as *Lolium perenne*, *Phalaris tuberosa*, and *Lolium subulatum*, all of which make relatively large demands upon soil fertility and whose culture is not, therefore, easy until the land has been through the initial phase of clover dominance.

district subterranean clover is often dominant on affected pastures, particularly in spring when the symptoms of disease are most noticeable. One such pasture, visited in September 1932, contained (per cent.): subterranean clover 70, perennial rye-grass 5, cocksfoot 5, Yorkshire fog 5, exotic annuals 5, other species 5. It had a ground cover of 100 per cent. and the clover leafage was about 9 inches high. Osteomalacia was acute in the dairy stock grazing upon it. From the British standpoint these pastures would in fact be considered too high in clover. The factors contributing to the 'Denmark' disease have not yet been elucidated. The feeding of crushed liver to affected stock has improved their health in certain instances. It has been suggested that the deficiency may be one of iron, or copper, or manganese [3]. Critical researches in this connexion are in progress [4]. An associated deficiency disease (bush-sickness) occurs in parts of New Zealand, also on clover-efficient pastures. Aston [5] has traced this to a deficiency of iron; the feeding of oxide of iron (limonite) as a stock-lick acts as a corrective, though this is not fully confirmed by the recent work of Rigg and Askew [6].

1. *Specific Legumes in relation to the Improvement of Australian Pastures*

Indigenous Legumes

The poorness of the Australian indigenous flora in herbaceous legumes has been noted; there were no indigenous species of either *Trifolium* (clovers) or *Medicago* (trefoils). As economic grazing plants, none of the indigenous herbaceous legumes is comparable with the introduced clovers and trefoils. Nor do they appear to grow profusely enough to have any material aggregate influence in building up soil fertility. Some of the indigenous species, especially species of *Glycine*, *Kennedya*, and *Vigna*, may, however, be worthy of further investigation, since they are much more widely distributed in Australia than are the exotic clovers and trefoils. Even in low-rainfall areas of the sub-interior, occasional plants of indigenous legumes may be found in the pastures.

Exotic Legumes

(*a*) *Annual Species.*—A number of annual legumes, particularly the clovers (*Trifolium* spp.) and trefoils (*Medicago* spp.), largely of south European origin, has been introduced into Australia. For the most part seeds of these plants have been introduced unwittingly, particularly in the early days of colonization. There is usually no exact record of the time or mode of introduction, but it is probable that they were imported as impurities in agricultural seeds or were carried in packing materials for long-distance sea transport. However introduced, these annuals have spread far and wide throughout temperate Australia. Individually, many of them are of low agricultural value and in their native habitats in Europe are regarded as roadside weeds. Having regard to the paucity of indigenous pasture legumes in primitive Australia there can be no doubt, however, that in the aggregate these introductions have played a most important part in laying the foundation of the pastoral industry in the Commonwealth. At least one of them, subterranean clover (*Trifolium subterraneum*), has proved to be of the greatest value in temperate districts, and is likely to become increasingly important in future pasture development. It is noteworthy that subterranean clover is regarded in Europe with no more interest than as a species to which occasional reference may be made in text-books. We find it growing wild in Britain too, usually on poor sandy situations. In southern Australia it is the foundation-stone of the future development of intensive grassland farming.

Subterranean clover (*T. subterraneum*).—The culture of subterranean clover began in the Mount Barker district of South Australia. It is now grown widely in all the southern States, as well as on the southern Tablelands and the adjacent districts in New South Wales. Recent investigations have shown that agronomically there are at least three main types of this clover as classified on the basis of date of flowering. These forms are (*a*) early flowering, (*b*) mid-season, and (*c*) late flowering. The Mount Barker type belongs to the mid-season group, and since most of the seed which has become distributed throughout Australia is of Mount Barker origin, it follows naturally that the greater proportion

of Australian seed belongs to the mid-season group. Seed of both the early and the late forms is, however, now becoming available in commerce, whilst the Victorian Department of Agriculture is already marketing one of its selected strains under the name of 'Burnerang'.

The early-flowering forms of subterranean clover are more suitable than the late-flowering forms in districts of low rainfall. When they become generally available in commerce they will materially extend the potential range of conditions under which this clover can be cultivated. The mid-season forms are usually grown in districts having an annual rainfall greater than 20 inches. The early-flowering forms can probably be grown in districts with a rainfall as low as 15 inches.[1] They flower early enough in the spring to enable them to set seed before the dry and desiccating conditions of summer set in. Under conditions of good rainfall the late forms are likely to prove extremely valuable. They are very productive, form a very dense sward, and bear a high proportion of leaf. They have, therefore, the same general agronomic characters that we find in the late-flowering forms of white and red clovers. There are three major grassland associations on which subterranean clover is likely to take a prominent place in Australian pastures. These are: (*a*) perennial rye-grass, cocksfoot, with the late-flowering form of subterranean clover; (*b*) perennial rye-grass, *Phalaris tuberosa* with the mid-season form; (*c*) *Phalaris tuberosa*, Wimmera rye-grass and improved strains of *Danthonia* spp., with the early-flowering form.

Crimson clover (*Trifolium incarnatum*).—Crimson clover is not extensively grown in Australia except in the Scottsdale district (north-east Tasmania), where it takes a prominent place. It has been grown there for upwards of 20 years [8], and is employed largely for soil improvement; in addition the first harvest seed provides a valuable cash crop.

Other annual clovers.—Among the host of annual exotic clovers which have become secondarily indigenous in Australia the following are important:

Drooping-flowered clover (*T. cernum*).
Cluster clover (*T. glomeratum*).
Suckling clover (*T. minus*).
Hop clover (*T. procumbens*).
Reversed clover (*T. resupinatum*).

Seed of the first two species is available commercially, although cluster clover is not extensively sown. Drooping-flowered clover is cultivated in the south-west corner of the continent, where on wet, low-lying habitats it replaces subterranean clover. Cluster clover provides valuable spring-feed in areas of low rainfall. Suckling and hop clovers play a parallel role in districts of higher rainfall. Reversed clover (or 'annual strawberry clover', as it has also been aptly called) is distributed throughout the southern States, usually in damp hollows and often in association with perennial rye-grass, meadow foxtail, and Yorkshire fog in a habitat probably suitable for either white clover (*T. repens*) or strawberry clover (*T. fragiferum*).

[1] Early forms of subterranean clover have been grown at Dangin, Western Australia (average rainfall about 14 in. per annum).

None of the other annual clovers is as important as those already discussed, although in the aggregate their influence must have been great. They are: knotted clover (*T. striatum*), rough clover (*T. scabrum*), woolly clover (*T. tomentosum*), haresfoot clover (*T. arvense*), fine-leaved clover (*T. angustifolium*), stellate clover (*T. stellatum*), and suffocated clover (*T. suffocatum*). Of this list, haresfoot clover is probably the most abundant and widespread; although it is of relatively low intrinsic value its mere abundance gives it appreciable value in the aggregate.

Annual trefoils.—The annual trefoils (*Medicago* sp.) are extensively distributed and have spread into regions of lower rainfall more than the clovers. None of the annual trefoils is cultivated in Australia and seed is not commercially available. By far the most common species is the toothed burr (*M. denticulata*), but *M. minima* is also widespread and makes important contributions to herbage. Among other species of, perhaps, less importance in the natural grasslands are *M. maculata*, *M. laciniata*, *M. tribuloides*, *M. confinis*, *M. orbiculare*, *M. truncatula*, and *M. scutellata*. All these are of Mediterranean origin.

Other annuals.—There are three other annual legumes which may be noted here: *Melilotus officinalis* (= *M. parviflora*), *Lotus hispidus*, and *Trigonella* sp. Each is valuable in certain localized habitats. *Melilotus officinalis* has established itself on the coastal pastures of King Island (Tasmania) and has been of great benefit thereto. In dairying districts on the mainland, however, it is regarded as undesirable, since it taints both milk and butter. It is not a plant of high grazing value and its palatability is relatively low, but it is valuable as a pioneering legume which can freely establish itself on very poor grasslands and set in motion the first phases of pasture improvement.

Considering the tropical and sub-tropical agricultural belts of Australia, there are available remarkably few species of suitable legumes. There is none whose influence upon pasture development can so far be compared with that of subterranean clover in temperate Australia. Three species may be noted as being of special significance: wild lucerne (*Stylosanthes mucronata*, or *S. procumbens*), tick trefoil (*Desmodium triflorum*), and *Lespedeza striata*. The first named is definitely exotic, being native to tropical South America. The others are also probably exotic, but were introduced at an earlier date [9]. Wild lucerne[1] appears to be of promise, particularly on the tropical coast of northern Queensland. It was first recorded some years ago at Townsville (approx. lat. 19° S.). It has spread northwards at least as far as Port Douglas (approx. lat. 17° S.); south of Townsville it has been recorded around Mackay (lat. 21° S.). Here is an interesting example of a recent unbidden introduction (it is considerably less than 20 years since it was first noted at Townsville) which has spread over a distance of about 300 miles, north to south, on the Queensland coast. It does not yet appear to have materially invaded the pastures in this area, but is common along railway tracks, in station-yards, waste places, and near the sea wharves.[2]

[1] So called because of the similarity of its leafage to lucerne (*Medicago sativa*); botanically, of course, the two species have only a family connexion.

[2] Colonies of *Stylosanthes mucronata* forming small closed associations were also

Its spread on the Townsville Common is claimed to have resulted in a greatly increased stock-carrying capacity on that common.

No seed of wild lucerne is available in commerce. It has, however, been observed to seed freely, so that production of seed should present little difficulty. It is a summer-growing annual, its period of active growth synchronizing with the monsoonal rains. In view of the paucity of available legumes in north Queensland, the outcome of closer investigation of this species will be awaited with interest. The general behaviour of the plant seems to offer considerable promise, and there may be significance in the fact that it is so luxuriant in waste spots around the wharves and station-yards. Phosphates are seldom employed in north Queensland, except in growing sugar-cane. For this purpose they are transported to their destination by boat or rail, so that wharfsides and railway-sidings are likely to receive a certain amount (probably considerable in the aggregate) of spillings from the manure-bags. It is just where such spillings might be expected to accumulate that wild lucerne has been observed to form a dense turf. It is almost certain that the introduction of new legumes into tropical pastures would have to be supplemented by adequate manuring with phosphate. It must be emphasized that neither subterranean clover nor any other of the clovers made phenomenal spread in temperate Australia until phosphates had been applied. A closely comparable lesson is to be learnt on the Welsh hills.

(*b*) *Perennial Legumes.*—In contradistinction to the annual legumes already discussed, the perennial legumes have been designedly introduced into Australia as agricultural seed. With the exception of lucerne, which promises to be valuable in the sub-tropics and in favourable habitats even within the tropics, the introduced perennial pasture legumes are confined to temperate habitats in Australia.

Strawberry clover is widespread in damp situations and in districts of good rainfall. It is of particular importance in the valleys of Gippsland and on retentive soils in the western districts of Victoria. Important differences in strain occur and the species might well repay detailed study by the plant-breeder. For example, the form known in Australia as Shearman's clover is extremely productive on damp soils. On the other hand, colonies of a small-leaved rosette type have commonly been observed on dry banks in areas of much lower rainfall than is usually associated with strawberry clover.[1]

Red clover is employed extensively in admixture for pastures in the southern States and under irrigation. Broad red types have been used, and comparative tests between the broad, late, and extra-late (Montgomery) types might lead to extremely valuable results. Broad red clover is said to be of far greater persistency in Australia than in Britain, but critical observations made on a number of pastures suggest that

noted along railway tracks and in station-yards on the Atherton Tableland, a rich dairying district at 2,000–3,000 ft. elevation (approx. lat. 17° S.), and an area in which the scarcity of leguminous plants in the pastures is characteristic and presents an acute pasture problem.

[1] Examples were observed near Strathalbyn (S.A.), rainfall 19 in., and also near Geelong (Vic.), rainfall 18 in. per annum.

re-seeding plays an important part in the apparent 'persistency' of the stands. In the red-clover districts the establishment of shed seed can take place much more easily than on British pastures. It is frequently alleged that red clover does not set seed in Australia because of the absence of the humble bee (*Bombus* spp.). There is no doubt, however, that seed is freely set whatever the pollinating agents. Breakwell [10] records reasonably good yields of seed from red clover in New South Wales. Seed-heads containing ripe seed have been collected by the writer in all the States, one such sample coming from Queensland, a State in which red clover is very little grown.

White clover is a valuable component of irrigated pastures, in some of which it becomes too aggressive. It is also an important plant in non-irrigated country on the coast of New South Wales, in parts of the elevated tablelands (red loams) of New South Wales and Queensland as far north as the Atherton Tableland, and in certain districts of Victoria and in Tasmania. With reference to the distribution of contrasting strains of white clover in Australia it is noteworthy that in southern Tasmania, where the old penal settlements were established, the quasi-indigenous type seems to be akin to the Kentish wild white clover. On the other hand, the dominating type in Victorian and other old-established pastures under irrigation shows affinity to the large-leaved type from New Zealand [11], whilst the free-seeding European form appears to be more common in the dairying districts of both Victoria and New South Wales.

Black medic is of relatively minor importance, except on the northern tablelands of New South Wales, where it is used much in the same way as subterranean clover is used in southern districts of the same State. Locally, on the black basaltic soils, *M. lupulina* is the most important legume in improved grasslands. These soils are rich in calcium and have a high pH value. On the improved swards it associates well with *Phalaris tuberosa* and with tall fescue to form pastures of high stock-carrying capacity. It can also establish and maintain itself in the natural herbage on otherwise unimproved land.

Lucerne is among the most important of legumes in Australia. In temperate districts it is probably less important as a pasture plant than subterranean clover, but even here it is widely grown for fodder. Under conditions of low and erratic rainfall, particularly in New South Wales and parts of Queensland, lucerne seems to be the grazing plant *par excellence*. Lucerne is sown thinly at rates not greater than 4 lb. of seed per acre, experience showing that rates of from 1 to 2 lb. per acre give excellent results.[1] With proper attention to both management and manuring thinly-sown stands will last for years and provide an amazing amount of feed. If sown too thickly a dense stand of weakly plants is obtained, but these fail to survive the first drought, resulting in the total loss of the stand. It would seem that lucerne sown at low seed-rates provides the key to pasture improvement in sub-tropical areas with an average annual rainfall of 15 to 30 inches. There is little doubt that

[1] For obvious reasons, good germination and high purity are essential when low seed-rates of this order are employed.

lucerne growing can be greatly extended in the sub-interior of New South Wales and Queensland. An interesting practice on some stations is to grow lucerne for the express purpose of carrying the sheep in times of grass fire. The relatively green lucerne paddock provides a reasonably safe 'hospital' for the flock when the surrounding parched grasslands take fire.

2. *Increased Carrying-Capacity on Improved Pastures*

Appreciable increases in stock-carrying capacity are associated with the stimulation of legumes following dressings of from 1 to 2 cwt. of superphosphate to the acre. The general practice is to apply phosphate at about these rates every one, two, or three years: the more frequent the application usually the smaller is the rate at which it is applied. Table 1 shows the aggregate botanical composition based on records from three centres in New South Wales [12]. These figures will serve to summarize the general influence of phosphates upon the botanical composition of top-dressed natural pastures in southern Australia. In their unimproved state pastures of this type will carry about one sheep to 1 or 1½ acres; top-dressing with phosphatic fertilizer, with no sowing of 'seeds', increases the carrying capacity by approximately 60 per cent. [13, 14].

TABLE 1. *Botanical Composition of Natural Pastures, (a) Unmanured, (b) Treated with Phosphate. Average of Three Centres, based on Published Data* [12]

	Natural pasture	
	Unmanured	*Treated with phosphate*
	per cent.	per cent.
Exotic legumes . .	24	52
Native grasses . .	18	16
Exotic grasses . .	18	14
Other plants . .	40	18
Total	100	100

When the use of phosphate is accompanied by the sowing of subterranean clover, the carrying capacity is increased still further, and the change in botanical composition is even more marked. On highly improved pastures in which subterranean clover is dominant, the carrying capacity is often increased by 400 per cent. above that of the unimproved land. Bevin [15] records that improved pastures of subterranean clover and perennial rye-grass in Tasmania carry the equivalent of about 7 ewes per acre, whilst the natural pastures in the same locality will carry not more than one sheep per acre. Numerous examples occur where the use of subterranean clover with superphosphate has resulted in six-fold and even eight-fold increases in carrying capacity. Table 2 is based on evidence from New South Wales [12], and shows the botanical composition of an unimproved pasture carrying about one sheep per acre, and

also the composition of a subterranean clover-pasture which carried four sheep per acre.

TABLE 2. *Aggregated Botanical Composition of Two Pastures at Crookwell, N.S.W.; (a) Unimproved, (b) Improved to Stage of Clover-dominance (based on Published Data* [12])

	Unimproved natural pasture (1 sheep per acre)	*Improved, clover-dominant (4 sheep per acre)*
Subterranean clover	..	60
Other legumes .	2	4
Native grasses .	40	14
Exotic grasses .	40	14
Other plants . .	18	8
Total	100	100

In the unimproved state the fertility of these soils is usually not high enough to carry rye-grass and other plants demanding high fertility. Subsequent to the period of dominance by subterranean clover and the resulting period of high general production, the fertility is raised and the edaphic condition is made suitable for the establishment of more valuable pasture grasses. Among the more promising of these, in districts of fair rainfall, are pasture strains of perennial rye-grass, *Phalaris tuberosa*, tall oat-grass (*Arrhenatherum avenaceum*), and tall fescue (*Festuca elatior* and *Schenodorus Hookerianus*). In belts of lower rainfall certain species of *Danthonia* are promising, but seed is not yet available in quantity. The annual, Wimmera rye-grass, plays a part of ever-increasing importance in pasture improvement on the self-mulching soils.

The extending practice of sowing lucerne at low seed-rates has been discussed. A large number of records detailing relative carrying-capacities are available in the various agricultural journals. Lucerne as a grazing plant and land improver finds its greatest application in central New South Wales and other districts in which subterranean clover cannot be grown. Mau [16] records a carrying-capacity of two sheep per acre on thinly-sown lucerne at Bathurst. This compares with less than one sheep per acre on the local natural pastures. Whittet [17] showed that an average stocking of 1·96 sheep per acre was obtained on lucerne at Trangie (average rainfall 14 in.) as against 0·5 sheep per acre on the unimproved pastures, a fourfold increase. Similar records have been obtained with lucerne (sown at very low seed-rates) at Roma in the Queensland sub-tropics with a rainfall of 23 inches.

3. *Discussion*

Emphasis has been laid upon the important part played by leguminous plants in the improvement of Australian grasslands. In the southern temperate belt clovers take a prominent place in present-day pastures. Farther north in regions of more erratic rainfall and in the sub-tropics and tropics where the rains are largely of summer incidence, clovers do

not thrive. As pasture plants they become of gradually diminishing importance as one proceeds northwards. Lucerne and some of the other medics take up the running in central and northern districts of New South Wales and in southern Queensland. Lucerne provides the keynote to pasture development in these districts, just as subterranean clover does in southern districts. There appears to be no adequate reason why lucerne cultivated on the New South Wales system should not thrive much farther north in Queensland than the zone of its present-day culture.

On the dairy pastures of the Queensland coast there is a real need for an efficient and suitable leguminous pasture-plant. A similar need is arising in the sub-coastal belt of tropical Queensland. Lucerne may ultimately be the answer in sub-coastal areas, and *Stylosanthes mucronata* may provide the key legume on the coastal fringe itself. There still remain those vast tracts of natural savannah and treeless steppe in central and western tropical Queensland. The introduction of the right legume into these would influence an area of country nearly as large as western Europe and possibly transform its whole agricultural outlook. This might result in a complete change-over from the present extensive pastoral systems of agriculture to one at least less extensive in type. Such a transition would be the obvious outcome of increased pasture production and lead to an increased population, both animal and human.

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INVESTIGATIONS OF THE MANURIAL EFFECTIVENESS OF AMMONIUM PHOSPHATE

Pt. II. EXPERIMENTS IN THE BRITISH ISLES TO COMPARE CONCENTRATED FERTILIZERS CONTAINING AMMONIUM PHOSPHATE WITH ORDINARY MIXTURES CONTAINING SUPERPHOSPHATE

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A GENERAL discussion and review of the literature on the value of ammonium phosphates as fertilizers has been given in the preceding paper [1]. To obtain information on the value of ammonium phosphates in the British Isles a number of experiments has been conducted by the Agricultural Research Department of Imperial Chemical Industries, Ltd. since 1927; a few were carried out at Jealott's Hill and a much larger number at outside centres.

Experiments at Jealott's Hill

The results of the experiments at Jealott's Hill[1] are given in Table 1, and show that Nitrophoska (based on diammonium phosphate), the concentrated fertilizers based on monammonium phosphate, and the ordinary mixtures of sulphate of ammonia, superphosphate, and muriate of potash all gave approximately the same results in every experiment. The soils at Jealott's Hill and Melchet Court were approximately neutral in reaction.

Experiments at Outside Centres

These experiments were scattered over the British Isles and, hence, covered a wide range of climatic and soil conditions. The crops experimented on were oats, potatoes, sugar-beet, and mangolds.

At all centres a mixture composed of ammonium sulphate, monammonium phosphate, and a potash salt was compared with an ordinary mixture of ammonium sulphate, superphosphate, and a potash salt giving the same amounts of N, P_2O_5, and K_2O per acre. Ammonium sulphate was included in the ammonium-phosphate mixtures, since the N : P_2O_5 ratio of monammonium phosphate (1 : 5 approx.) was too wide for the crops grown. The source of potash was the same in both sets of mixtures.

Mixtures of the same N : P_2O_5 : K_2O ratio were used at a large number of centres and were applied at the same rate. Since the aim of the experiments was to compare the effects of the same plant-foods in different forms, it is of minor importance that the amounts of N, P_2O_5, and K_2O used were not necessarily optimal for each particular set of conditions under which an experiment was conducted.

[1] Several fertilizer treatments were compared in all the experiments, but for the sake of simplicity results are given only for Nitrophoska, the concentrated fertilizer based on monammonium phosphate, and the ordinary mixture of ammonium sulphate, superphosphate, and potash.

TABLE 1. *Experiments with Nitrophoska, C.C.F.,* and Ordinary Mixture made at Jealott's Hill (and Melchet Court)*

Year	Rate of application (lb. per acre) N	P_2O_5	K_2O	Crop	Mean yield with Nitrophoska	C.C.F.*	Ordinary mixture	Standard error of mean yield
1928	23	23	28	Barley:				
				Grain (cwt./acre) . .	17·01	16·79	16·92	0·67
				Straw ,, . .	21·69	21·56	21·04	1·20
1929	34·5	34·5	42	Barley:				
				Grain (cwt./acre) . .	30·39	31·00	31·80	1·10
				Straw ,, . .	44·54	45·00	45·86	0·84
1929	46	46	56	Wheat:				
				Grain (cwt./acre) . .	27·75	25·77	26·08	0·50
				Straw ,, . .	44·18	42·25	44·18	0·51
1930	46	46	56	Wheat:				
				Grain (cwt./acre) . .	36·48	36·20	36·50	0·83
				Straw ,, . .	67·50	66·61	68·45	1·35
1927†	70	45	123	Potatoes (tons/acre) . .	8·87	..	8·74	0·35
1928	42	31	74	Potatoes (tons/acre) . .	14·40	..	13·79	0·38
1929	69	51	122	Potatoes (tons/acre) . .	10·11	10·95	11·30	0·34
1930	69	51	122	Potatoes (tons/acre) . .	12·46	12·36	12·37	0·26
1928	50	37	89	Sugar Beet:				
				Washed Beet (tons/acre) .	11·91	12·89	12·94	0·39
				Sugar content: % . .	17·19	17·50	17·44	..
				Sugar: (tons/acre) . .	2·05	2·26	2·26	..
1929	58	42	102	Sugar Beet:				
				Washed Beet (tons/acre) .	14·66	13·90	14·72	..
				Sugar: (tons/acre) . .	2·83	2·71	2·77	0·12
1930	58	42	102	Sugar Beet:				
				Washed Beet (tons/acre) .	11·54	11·56	11·74	..
				Sugar content: % . .	19·2	19·3	19·7	..
				Sugar: (tons/acre) . .	2·22	2·23	2·32	0·06
1931	69·2	69·2	82·7	Sugar Beet:				
				Washed Beet (tons/acre) .	..	11·85	11·62	1·22
				Sugar content: % . .	..	19·64	19·32	0·67
				Sugar: (tons/acre) . .	..	2·33	2·25	0·26
				Tops: (tons/acre) . .	..	9·4	9·9	1·31

* C.C.F. = concentrated complete fertilizer with monammonium phosphate as basis.
† Melchet Court, Hants.

In the sugar-beet experiments a no-fertilizer treatment was included at all but two centres, since it would have been of little use to compare two fertilizers unless one or both could be shown to have caused an increase in yield. In many of the experiments other treatments were also included, but are not reported as they have no immediate bearing on the subject under consideration.

In the 1930 experiments the ammonium-phosphate mixtures were home-made and consisted of ammonium sulphate, monammonium phosphate, and a potash salt, but in the 1931 and 1932 experiments the ammonium-phosphate fertilizers were commercially prepared granular products.

Results.—The average results are given in Table 2, and the results of individual experiments in Tables 3–5.

From Table 2 it will be seen that the average results for oats, potatoes, and sugar-beet were practically identical with the ammonium-phosphate mixture and the ordinary mixture.

Experiments in 1930.—It might be assumed from the results given in Tables 3–5 that the two fertilizer mixtures behaved differently at certain centres. In the 1930 and 1931 experiments the lay-outs were all 3×3

TABLE 2. *Average Yields with Ammonium Phosphate and Ordinary Fertilizer on Oats, Potatoes, and Sugar-Beet at Outside Centres*

Crop	*Year*	*No. of centres*		*No fertilizer*	*Ammonium phosphate mixture*	*Ordinary fertilizer*
Oats. .	1930	13	Grain: cwt./acre . .	19·17	26·45	26·45
			Straw: ,, . .	23·24	30·96	30·90
Potatoes .	1930	14	Tons/acre . . .	7·05	12·89	12·64
	1931	4	,, . . .	9·82	12·30	12·30
	1932	14	,, . . .	8·87	12·32	12·22
	Mean	32		8·19	12·57	12·42
Sugar-Beet	1930	13	Roots: tons/acre . .	8·55	12·14	12·03
		13	Sugar: ,, . .	1·50	2·13	2·18
		12	Tops: ,, . .	7·81	10·78	10·63
		13	Sugar: % . .	17·45	17·42	17·42
	1931*	7	Roots: tons/acre . .	10·74	12·21	12·19
		7	Sugar: ,, . .	1·94	2·22	2·25
		7	Tops: ,, . .	11·73	14·04	13·91
		7	Sugar: % . .	17·98	18·27	18·37
	1932	10	Roots: tons/acre . .	10·03	11·91	11·96
		10	Sugar: ,, . .	1·74	2·08	2·09
		7	Tops: ,, . .	9·04	11·71	11·89
		10	Sugar: % . .	17·25	17·46	17·49
	Mean†	30	Roots: tons/acre . .	9·47	12·08	12·04
		30	Sugar: ,, . .	1·66	2·13	2·14
		26	Tops: ,, . .	8·99	11·91	11·85
		30	Sugar: % . .	17·47	17·63	17·67

* 5 centres for 'no fertilizer'.
† 28 centres for 'no fertilizer', except tops where number is 24.

Latin squares, and although it is, of course, impossible to interpret statistically the results of a single 3×3 Latin-square experiment, since the error is based on two degrees of freedom only, a composite analysis of the results of a number of such simple experiments can be legitimately made, provided that the distribution of the mean error variance is appreciably the same as that of χ^2 for the appropriate number of degrees of freedom, i.e. the errors must be homogeneous.

From Table 6 it will be seen that a composite analysis of the results of the 1930 experiments is justified only for oat-straw, but here the ammonium-phosphate mixture and the ordinary mixture have not behaved differently at different centres ($z = 0{\cdot}1164$; at 5 per cent. point $z = 0{\cdot}3823$). The distribution for sugar-beet tops shows so many 'tails' that a composite analysis of the results is obviously unwarranted. By omitting the 'tails' of the distributions given in Table 6 for oat-grain, potatoes, and sugar-beet roots,[1] the distributions appear more or less reasonable, but the numbers of centres left are rather small for the method of testing, and since none of the z values for comparison of the ammonium-phosphate mixture and ordinary mixture for individual centres approaches the 5 per cent. point and only a few are of any size, it is reasonable to conclude that those relatively large differences which occurred were associated with high errors, i.e. the results with the two mixtures on oats, potatoes, and sugar-beet did not differ significantly at any centre.

[1] A statistical comparison of the percentage sugar-content and yield of sugar at individual centres in 1930 and 1931 is impossible, since the percentage sugar-content was determined on composite treatment-samples.

TABLE 3. *Average Yields with Ammonium-Phosphate Mixture and Ordinary Fertilizer on Oats*

Fertilizer Basis: 3 cwt. per acre of ammonium-phosphate mixture (N 9·88%, P_2O_5 18·63%, K_2O 10·56%)

No.	Centre	Soil		Grain			Straw		
		Type	pH	No fertilizer cwt./acre	Ammonium-phosphate mixture cwt./acre	Ordinary fertilizer cwt./acre	No fertilizer cwt./acre	Ammonium-phosphate mixture cwt./acre	Ordinary fertilizer cwt./acre
1	Winterbourne, Hants	Light loam	7·04	17·97	24·29	24·88	18·09	26·55	26·19
2	Severnhampton, Wilts.	Medium-heavy loam	7·50	16·54	25·47	23·93	18·93	27·14	25·0
3	Stoke-by-Clare, Suffolk	Medium loam	7·39	21·07	26·43	25·59	21·07	26·43	25·59
4	Gt. Abington, Cambridge	Gravelly loam	7·45	12·14	18·45	18·09	13·80	22·60	22·02
5	Rainford, Lancs.	Dark sand	4·89	23·68	31·43	35·53	27·97	36·90	40·71
6	Moortown, Leeds	Heavy loam	6·70	6·79	11·67	11·60	15·83	21·19	20·77
7	Mains of Penmure, Carnoustie	Heavy loam	6·44	26·25	34·94	32·74	32·86	40·95	36·43
8	Balwyllo, Montrose	Medium loam	5·20	23·45	34·94	33·45	26·31	34·76	33·33
9	Gallaton, Stonehaven	Heavy loam	5·73	25·11	34·80	34·75	22·97	30·00	30·36
10	Dunnator Mains, Stonehaven	Black loam	4·89	26·96	31·90	34·28	25 71	30·00	32·62
11	Ballybit, co. Carlow	Heavy loam	4·98	20·54	23·99	22·98	31·07	44·64	44·40
12	Levitstown, co. Kildare	Medium loam	6·22	11·01	17·86	18·57	18·45	25·83	25·36
13	Ballyvourisheen, co. Cork	Gravelly loam	7·78	17·68	28·04	27·44	29·04	35·47	38·93

TABLE 4. *Average Yields with Ammonium-Phosphate Mixture and Ordinary Fertilizer on Potatoes*

Fertilizer Basis:

1930. 6 cwt. per acre of ammonium-phosphate mixture (N 11·01 %, P_2O_5 11·94 %, K_2O 20 %)
1931. 5 cwt. per acre of ammonium-phosphate mixture (N 12·5 %, P_2O_5 12·5 %, K_2O 15 %)
1932. 6 cwt. per acre of ammonium-phosphate mixture (N 10·4 %, P_2O_5 10·4 %, K_2O 20·8 %)

Year and No.	*Centre*	*Soil*		*No fertilizer* tons/acre	*Ammonium-phosphate mixture* tons/acre	*Ordinary fertilizer* tons/acre	*Significant difference* ($P = 0.05$)	*Lay-out*
		Type	*pH*					
1930, 1	Colnbrook, Bucks.	Dark loam	7·5	12·36	20·46	17·40	..	3 × 3
2	Shifnal, Salop.	Sandy loam	6·67	8·04	13·95	13·46	..	3 × 3
3	Welton Cliff, Lincoln	Limestone	7·88	7·07	10·58	10·52	..	3 × 3
4	Selby, Yorks.	Medium loam	5·74	2·31	10·70	9·29	..	3 × 3
5	Ormskirk, Lancs.	Medium loam	5·54	5·07	12·01	12·00	..	3 × 3
6	Durham	Medium loam	7·00	2·08	11·10	11·23	..	3 × 3
7	Irvine, Ayrshire	Medium loam	4·68	10·50	16·00	16·20	..	3 × 3
8	Bonyton, Linlithgow	Medium loam	7·99	7·30	13·40	13·80	..	3 × 3
9	Glencarse, Perthshire	Medium loam	6·01	5·37	9·80	10·36	..	3 × 3
10	Lossiemouth, Elgin	Light loam	4·73	9·50	12·51	12·57	..	3 × 3
11	Ballymena, co. Antrim	Medium loam	5·38	5·96	10·11	10·08	..	3 × 3
12	Downpatrick, co. Down	Medium loam	6·07	6·64	12·17	12·65	..	3 × 3
13	Ballyward, co. Down	Sandy	4·87	7·30	12·59	12·51	..	3 × 3
14	Castlebellingham, co. Louth	Heavy loam	5·32	9·17	15·05	14·95	..	3 × 3
1931, 15	King's Lynn, Norfolk	Heavy loam	7·90	13·06	14·40	14·31	..	3 × 3
16	King's Lynn, Norfolk	Heavy loam	?	8·27	10·61	10·63	..	3 × 3
17	Rainham, Essex	Heavy clay	7·85	7·95	11·37	11·45	..	3 × 3
18	Rochford, Essex	Heavy clay	6·40	9·99	12·80	12·80	..	3 × 3
1932, 19	Worksop, Notts.	Sandy	6·46	8·54	11·31	11·12	0·83	5 × 5
20	Rainford, Lancs.	Medium peaty	5·37	5·36	11·74	11·57	0·48	5 × 5
21	Ormskirk, Lancs.	Medium loam	6·70	8·63	15·27	15·44	0·78	4 × 4
22	Milford, Surrey	Medium loam	6·86	10·81	14·95	14·72	0·77	5 × 5
23	Churt, Surrey	Sandy	6·14	6·84	10·71	10·95	0·64	5 × 5
24	Stonesfield, Oxon.	Medium-heavy loam	8·51	7·79	9·54	9·53	0·67	5 × 5
25	Wyboston, Beds.	Heavy loam	6·14	12·14	12·78	12·93	0·82	4 × 4
26	Milton, Cambs.	Light loam	7·62	6·26	10·13	9·93	1·18	4 × 4
27	Knutsford, Cheshire	Light loam	6·15	12·62	17·20	17·33	0·76	4 × 4
28	Lichfield, Staffs.	Sandy	6·19	9·94	14·00	14·42	0·74	4 × 4
29	Carrington, Lancs.	Medium peaty	5·77	13·24	14·63	14·36	2·44	5 × 5
30	Bovey Tracey, Devon	Light peaty	5·84	5·98	10·15	10·10	0·49	4 × 4
31	Redbourne, Lincs.	Medium loam	8·52	7·54	8·99	8·58	0·70	4 × 4
32	Scunthorpe, Lincs.	Heavy loam	8·28	8·55	10·98	10·15	1·36	4 × 4

Centre 29: 14 tons dung applied per acre. Centre 30: Fertilizer basis: 8 cwt. per acre of ammonium phosphate mixture (N 10·4%, P_2O_5 10·4%, K_2O 20·8%).
,, 24: 12 ,, ,, ,, ,, 31: ,, ,, 12 ,, ,, ,, ,, (N 12·5%, P_2O_5 12·5%, K_2O 15%).
,, 27: 18 ,, ,, ,, ,, 32: ,, ,, 6 ,, ,, ,, ,, (N 12·5%, P_2O_5 12·5%, K_2O 15%).

TABLE 5. *Average Yields with Ammonium-Phosphate Mixture and Ordinary Fertilizer on Sugar-Beet*

Fertilizer Basis:

1930. 5 cwt. per acre ammonium-phosphate mixture (N 11·01%, P_2O_5 11·94%, K_2O 20%)
1931. 5 cwt. per acre ammonium-phosphate mixture (N 12·5%, P_2O_5 12·5%, K_2O 15%)
1932. 4 cwt. per acre ammonium-phosphate mixture (as in 1931)

Year and No.	Centre	Soil: Type	Soil: pH	Roots: No fertilizer tons/acre	Roots: Amm.-phos. mixture tons/acre	Roots: Ordinary fertilizer tons/acre	Roots: Sig. diff. ($P=0{\cdot}05$) tons/acre	Sugar-content: No fertilizer %	Sugar-content: Amm.-phos. mixture %	Sugar-content: Ordinary fertilizer %	Sugar-content: Sig. diff. ($P=0{\cdot}05$)	Tops: No fertilizer tons/acre	Tops: Amm.-phos. mixture tons/acre	Tops: Ordinary fertilizer tons/acre	Sugar: No fertilizer tons/acre	Sugar: Amm.-phos. mixture tons/acre	Sugar: Ordinary fertilizer tons/acre	Sugar: Sig. diff. ($P=0{\cdot}05$) tons/acre	Lay-out
1930, 1	St. Issey, Cornwall	Light	6·12	7·44	15·69	13·75	..	16·7	17·3	16·4	..	8·07	12·44	9·57	1·24	2·71	2·26	..	3×3
2	Bideford, Devon	Medium loam	7·85	7·19	12·28	11·32	..	18·9	18·1	18·3	..	3·66	6·15	6·41	1·36	2·22	2·07	..	3×3
3	North Hayling, Hants	Brick earth	7·62	10·07	13·93	13·10	..	18·6	18·3	18·2	..	5·01	6·71	7·08	1·87	2·55	2·38	..	3×3
4	Hadleigh, Suffolk	Clay loam	7·12	7·74	10·97	11·89	..	17·5	17·3	17·5	..	10·04	14·06	14·27	1·35	1·90	2·08	..	3×3
5	Hockwold, Norfolk	Light loam	7·85	11·88	13·96	15·06	..	16·9	16·7	17·2	..	8·63	9·27	9·95	2·01	2·33	2·59	..	3×3
6	Kettering, Northants.	Medium loam	7·66	11·94	14·35	14·36	..	18·8	18·5	19·0	..	7·67	8·24	9·29	2·24	2·65	2·73	..	3×3
7	Bridgnorth, Salop.	Sandy gravel	5·53	6·2	10·27	10·02	..	15·7	16·8	16·9	..	3·49	6·05	5·63	0·97	1·73	1·69	..	3×3
8	Selby, Yorks.	Clay loam	5·05	8·99	11·17	11·47	..	18·3	18·7	17·9	..	9·79	14·07	12·40	1·65	2·09	2·05	..	3×3
9	Heslington, Yorks.	Medium loam	5·88	9·46	12·54	12·46	..	17·6	17·4	17·5	..	7·64	11·89	11·90	1·66	2·18	2·18	..	3×3
10	Newton-on-Ouse, Yorks.	Clay loam	5·82	7·42	10·93	10·79	..	16·4	16·6	16·5	..	7·11	10·52	10·60	1·22	1·81	1·78	..	3×3
11	Driffield, Yorks.	Light loam	7·10	3·70	5·46	5·38	..	16·0	15·4	15·5	..	..	..	..	0·59	0·84	0·83	..	3×3
12	Tinryland, Carlow	Clay	6·15	9·62	12·72	13·01	..	17·3	17·3	17·4	..	14·49	18·48	18·11	1·66	2·20	2·26	..	3×3
13	Goresbridge, co. Kilkenny	Clay loam	7·68	9·47	13·53	13·72	..	18·1	18·1	18·2	..	8·09	11·48	12·39	1·71	2·45	2·50	..	3×3
1931, 14	Norwich	Light loam	8·0	6·61	8·98	8·49	..	16·3	16·3	16·3	..	7·09	9·85	9·60	1·08	1·46	1·38	..	3×3
15	Norwich	Heavy loam	7·4	..	10·76	10·84	..	..	18·6	18·6	..	..	11·85	11·26	..	2·00	2·02	..	3×3
16	Ipswich	Heavy loam	7·6	12·90	15·40	15·51	..	18·0	19·1	18·5	..	10·59	13·53	13·46	2·32	2·94	2·87	..	3×3
17	Ipswich	Sandy	7·6	11·94	12·87	13·42	..	18·5	18·4	18·8	..	9·26	13·21	13·03	2·21	2·37	2·52	..	3×3
18	Rochford, Essex	Heavy clay	7·1	12·96	13·83	13·57	..	17·3	17·0	17·3	..	23·69	26·48	26·03	2·24	2·35	2·35	..	3×3
19	Downham Market	Light loam	7·4	9·29	11·55	11·57	..	19·8	18·9	19·4	..	8·03	11·75	12·69	1·84	2·18	2·24	..	3×3
20	Bury St. Edmunds	Heavy loam	7·8	..	12·11	11·91	..	..	19·6	19·7	..	..	11·61	11·24	..	2·25	2·35	..	3×3
1932, 21	Bridgnorth, Salop.	Light gravel	6·85	5·05	9·24	9·36	1·61	17·8	18·7	18·7	0·7	5·0	8·5	8·4	0·91	1·73	1·76	0·31	5×5
22	Worfield, Salop.	Sandy loam	7·17	13·30	16·26	16·00	0·65	17·1	17·6	17·7	0·45	..	..	..	2·28	2·86	2·83	0·13	4×4
23	Knettishall, Norfolk	Sandy	6·14	12·79	15·26	14·51	2·14	17·1	17·1	17·6	0·8	..	..	..	2·19	2·61	2·55	0·39	5×5
24	Chaddesley, Worcs.	Sandy loam	7·50	6·03	8·07	8·27	0·92	17·4	17·9	17·7	0·19	6·9	11·4	10·5	1·05	1·44	1·46	0·20	4×4
25	Hagley, Worcs.	Medium loam	6·97	8·65	9·33	9·60	0·99	17·4	17·5	17·9	0·22	9·4	11·6	12·0	1·51	1·63	1·72	0·22	4×4
26	Isle of Wight	Medium loam	7·98	10·76	12·21	12·29	0·96	16·9	16·6	16·4	0·8	12·2	14·1	13·3	1·82	2·03	2·02	0·18	5×5
27	Hayling Island, Hants	Heavy silt	6·46	6·70	10·02	10·83	1·58	16·2	16·9	16·7	0·6	7·2	10·2	12·5	1·09	1·70	1·84	0·31	3×6
28	Kelvedon, Essex	Heavy clay	7·74	12·99	13·21	12·89	0·48	17·2	17·2	16·6	0·7	11·5	13·7	14·0	2·25	2·28	2·14	0·06	4×4
29	Bury St. Edmunds	Light loam	6·31	11·52	12·56	12·79	0·53	18·2	17·5	18·2	0·6	..	..	..	2·10	2·20	2·33	0·11	4×4
30	Kirton-in-Lindsey, Lincs.	Medium loam	6·64	12·49	12·91	13·04	0·93	17·2	17·6	17·4	0·73	11·1	12·5	12·5	2·15	2·27	2·27	0·18	4×4

Centre 23. 10 tons dung and 6 cwt. kainit applied per acre.
Centre 28. 10 tons dung applied per acre.

TABLE 6. *Distribution of Errors*

		P	*1·0*	*0·99*	*0·98*	*0·95*	*0·90*	*0·80*	*0·70*	*0·50*	*0·30*	*0·20*	*0·10*	*0·05*	*0·02*	*0·01*	*0·0*
Oats	Grain:	Actual	1	1	2	0	0	0	1	4	1	0	1	2	0	0	
		Expected	0·13	0·13	0·39	0·65	1·3	1·3	2·6	2·6	1·3	1·3	0·65	0·39	0·13	0·13	
	Straw:	Actual	0	0	0	2	1	1	2	3	2	1	0	1	0	0	
		Expected	0·13	0·13	0·39	0·65	1·3	1·3	2·6	2·6	1·3	1·3	0·65	0·39	0·13	0·13	
Potatoes:		Actual	1	0	0	2	3	1	2	1	0	2	1	0	1	0	
		Expected	0·14	0·14	0·42	0·70	1·4	1·4	2·8	2·8	1·4	1·4	0·70	0·42	0·14	0·14	
Sugar-Beet	Roots:	Actual	1	1	1	0	0	1	3	3	0	1	1	1	0	0	
		Expected	0·13	0·13	0·39	0·65	1·3	1·3	2·6	2·6	1·3	1·3	0·65	0·39	0·13	0·13	
	Tops:	Actual	1	2	0	3	2	0	1	0	0	0	2	0	0	1	
		Expected	0·12	0·12	0·36	0·60	1·2	1·2	2·4	2·4	1·2	1·2	0·60	0·36	0·12	0·12	

Experiments in 1931.—In the 1931 experiments on potatoes and sugar-beet the results with the ammonium-phosphate mixture and the ordinary mixture were practically identical at all centres, and any attempt to prove that the two mixtures behaved differently at different centres is obviously unwarranted.

Experiments in 1932.—The 1932 experiments on potatoes and sugar-beet were so designed that each could be analysed statistically. The differences between the ammonium-phosphate mixture and the ordinary mixture are in all cases very small, and none is significant.

Mangolds

Whilst the experiments described above afford no evidence of any adverse effect of ammonium phosphates on oats, potatoes, and sugar-beet, such mixtures were found to cause injury to mangolds under certain conditions. For this reason the experiments on mangolds will be considered separately.

Before giving the results it may be well to recapitulate briefly the conditions under which monammonium phosphate might cause injury. Although *free ammonia toxicity* might occur on very alkaline soils of low adsorptive capacity, *physiological toxicity* of *ammonium ions* on sandy soils deficient in calcium is more likely. Phosphate toxicity may also occur. Dangers due to temporary increases in soil acidity (exchange acidity) and injury to germination by plasmolysis appear to be at least as great with ordinary mixtures of ammonium sulphate and super-phosphate.

Since 1930 a number of cases of reduced numbers of plants per acre with ammonium phosphate mixtures[1] on mangolds have been brought to the authors' notice. Whilst many of these cases could be ascribed to damaged germination due to plasmolysis (often owing to improper use of combined fertilizer and seed drills) and would probably have occurred to at least the same extent with equivalent ordinary mixtures, certain cases in Devon and Cornwall afforded evidence that ammonium-phosphate mixtures had caused the death of young seedlings. Germination did not appear to be affected, but a very marked check in growth of some of the seedlings occurred, the cotyledons and young leaves becoming yellowish, and some of the seedlings dying, the number of deaths varying widely from place to place. Ordinary mixtures appeared to cause no such injury.

Where injury occurred it was usually found that the soils were markedly acid (pH usually below 5·5) and sandy in texture. In some cases the fertilizer was applied broadcast, in some the fertilizer and seed were sown down the same spout of a coulter drill, and in others the seed was sown in shallow, wide drills by means of a canister drill and the fertilizer was applied by hand along the rows and immediately on the seed. The use of canister drills is quite common in Devon and Cornwall.

To obtain further information on this question seven replicated experi-

[1] As in the earlier part of this paper this term is used to denote mixtures based on monammonium phosphate.

TABLE 7. *Experiments with Mangolds*

No.	Centre	Year	Fertilizers applied	Replication	Soil		Yields: tons per acre						Number of plants per acre					
					Type	pH	No fert.	Amm.-phos. mixt.	Ord. mixt.	Amm.-phos. mixt. + $CaCO_3$	Amm.-phos. mixt. + $CaSO_4$	Sig. diff.*	No fert.	Amm.-phos. mixt.	Ord. Mixt.	Amm.-phos. mixt. + $CaCO_3$	Amm.-phos. mixt. + $CaSO_4$	Sig. diff.*
Non-acid soils																		
1	Plymstock	1932	Broadcast	4	Medium-heavy loam	8·1	38·63	45·15	43·40	..	..	3·28	21,600	20,800	22,600	..	..	3,097
2	Penzance	1933	Broadcast	4	Light loam	7·1	54·9	60·4	60·1	..	..	2·6	21,600	22,300	21,900	..	..	1,000
Acid soils																		
3	Zelah	1933	Canister-drill	4	Medium loam	6·6	18·0	29·5	29·3	..	..	5·7	19,300	21,900	21,600	..	..	1,800
4	St. Neot	1932	Canister-drill	5	Light loam	5·7	21·48	37·25	44·71	45·61	42·71	3·93	23,700	28,700	31,400	30,800	29,900	4,300
5	Mabe	1933	Canister-drill	5	Light medium loam (peaty)	6·0	37·7	41·6	41·9	45·3	41·4	4·6	22,800	20,800	23,100	23,500	22,800	1,800
6	St. Keverne	1933	Canister-drill	5	Medium loam	5·6	54·0	62·2	62·2	64·8	62·9	3·3	18,000	20,100	19,200	20,200	19,800	2,200
7	Helston	1933	Coulter-drill	5	Medium loam	6·1	16·4	32·0	32·0	32·9	31·2	3·2	17,600	26,000	25,000	25,700	24,800	1,800

* For $P = 0{\cdot}05$; applicable to differences between *single* entries in Table.

ments were conducted on mangolds in Devon and Cornwall. In four of the experiments, on acid soils, the effects of additions of finely-divided calcium carbonate and calcium sulphate (gypsum) to the ammonium-phosphate mixtures were studied.

In all the experiments the same rates of application of fertilizers were used, the standard rate being equivalent to 6 cwt. per acre of an ammonium-phosphate mixture containing N 12·5 per cent., P_2O_5 12·5 per cent., and K_2O 15 per cent., and composed of monammonium phosphate, ammonium sulphate, and potassium sulphate and chloride. The ordinary mixture consisted of sulphate of ammonia, superphosphate (13·73 per cent. w.s. P_2O_5) and potassium sulphate and chloride. The calcium carbonate and gypsum were applied at rates to supply the same amount of calcium as was contained in the superphosphate of the ordinary mixture (1·55 cwt. CaO per acre).

Dung was applied at centres 1, 4, 5, and 6. At centres 2 and 6 the soil was in extremely good heart. The results obtained are given in Table 7.

Non-acid soils.—In the two experiments on non-acid soils, the small differences in yield and number of plants per acre on the plots treated with the ammonium-phosphate mixture and the ordinary mixture were insignificant. In these experiments the fertilizers were broadcast.

Acid soils.—At centre 7, where a coulter-drill was used, the soil fell back on the seed, and the fertilizers, which were sown by hand on the plots, were only in direct contact with the seed in a few isolated spots. (In practice the contact between seed and fertilizer is very close with a combined drill of this type.) The yields and numbers of plants per acre with the ammonium-phosphate mixture and the ordinary mixture did not differ significantly. Neither calcium carbonate nor calcium sulphate had a significant effect on the results.

At centres 3, 4, 5, and 6 a canister-drill was used, and the fertilizers came in direct contact with the seed.

At centre 3, where the soil was only slightly acid and the effects of adding calcium salts were not studied, the yields and number of plants per acre with the ammonium-phosphate mixture and the ordinary mixture did not differ significantly.

At centre 4 the yield with the ammonium-phosphate mixture was significantly lower than that with the ordinary mixture. The addition of either calcium carbonate or gypsum to the ammonium-phosphate mixture significantly increased the yield. Although the number of plants per acre with the ammonium-phosphate mixture was considerably lower than with the ordinary mixture or with the ammonium-phosphate mixture plus calcium carbonate or gypsum, the differences are not significant.

At centres 5 and 6 the yields with the ammonium-phosphate mixture did not differ significantly from those with the ordinary mixture. At centre 5, but not at centre 6, the number of plants per acre was significantly lower with the ammonium-phosphate mixture than with the other fertilizer treatments. In both experiments the yield with ammonium-phosphate mixture plus calcium carbonate was significantly greater than the average yield for the other three fertilizer treatments.

Whilst it is not claimed that the experiments described have dealt exhaustively with all the problems involved, they do show that on acid soils of low adsorptive capacity ammonium-phosphate mixtures may give definitely poorer results than equivalent ordinary mixtures when the fertilizers and seed are sown together in drills. In spite of the injury with the ammonium-phosphate mixtures, which occurred in the seedling stage and resulted in a reduction in the number of plants per acre in some but not all of the experiments, the yields with the ammonium-phosphate mixture were significantly greater than those with no fertilizer.

The results show that the injury to the seedlings was obviated by the addition of gypsum, whilst, on the acid soils, the application down the rows of a relatively small amount of calcium carbonate not only obviated injury with ammonium-phosphate mixtures but also resulted in an increased yield due to decreasing the acidity of the soil in the immediate vicinity of the plant-roots.

Although conditions were deliberately sought under which injury from the use of ammonium phosphate might be expected, in only one of the five experiments on acid soils was such injury revealed by the yields obtained, whilst in another a significant injury to plant numbers was not reflected in a reduced yield.[1] Thus, although such injury is liable to occur on light acid soils, it by no means always occurs even under these conditions.

The absence of any injury with ammonium-phosphate mixtures on the soils which were not both acid and of low adsorptive capacity is by no means conclusive proof that injury could not occur under these conditions, although on *a priori* grounds little or no injury would be expected. Although the effect of applying ammonium-phosphate mixtures broadcast on acid soils was not tested, the fact that a number of apparently authentic cases of injury on acid, sandy soils have been brought to the authors' notice, indicates that the danger exists, although, of course, to a smaller extent than when the fertilizer and seed are in close contact.

Summary

The results of a large number of experiments (75) conducted in the British Isles since 1930, on oats, potatoes, and sugar-beet, to compare the relative fertilizer value of ammonium-phosphate mixtures (mon-ammonium phosphate, sulphate of ammonia, and potash) and ordinary mixtures (sulphate of ammonia, superphosphate, and potash) are presented. The average results with the two mixtures are almost identical for all three crops. None of the differences between the two mixtures in individual experiments is significant.

Evidence is given showing that with mangolds on acid, sandy soils, ordinary mixtures were, in certain instances, though not always, superior

[1] An inverse relation between number of plants and size of individual plants is common; in the sugar-beet experiments described above it may be that in certain instances the numbers of plants per acre with the ammonium-phosphate mixture would, if counted, have been found to be lower than with the ordinary mixture. This effect, if it occurred, was not of practical importance, since it was not reflected in any reduction in yield.

to ammonium-phosphate mixtures. The ammonium-phosphate mixtures may cause the death of some seedlings. This injury was obviated by the presence of a small amount of gypsum (1·55 cwt. CaO per acre). The use of calcium carbonate, as well as obviating the injury with ammonium phosphate, resulted in a further substantial increase in yield when applied in the drills.

It appears that when such injury occurs with the ammonium-phosphate mixtures it is due to the presence of certain ions in physiologically toxic concentrations. The cations involved are those of ammonium, hydrogen, and potassium, of which the first is probably most important. Phosphate (H_2PO_4 ions) toxicity may also be a contributory factor.

Acknowledgements

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OAT-BREEDING IN SCOTLAND

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AT the Scottish Plant-Breeding Station work has been undertaken to procure improved varieties of spring-sown oats that would be especially adapted to different agricultural areas in Scotland. Requests are frequently made by progressive farmers for varieties that are adapted to certain sets of soil conditions. In some areas the importance of resistance to 'lodging' is strongly emphasized, especially in view of the extensive use of wild white clover, which has so enriched many temporary pastures that the immediately succeeding oat crop is very prone to lodge. In certain areas early-ripening types are desired; in others resistance to shedding of grain is required. Varieties showing improvements in any of these directions must also be highly productive and should have well-filled, thin-husked grain. The importance of the latter is often emphasized by oatmeal millers, who do not favour the large-grained, thick-husked varieties. In this connexion a director of a large firm of oatmeal millers has written as follows: 'There is a tendency now amongst farmers to grow very coarse, rough-skinned oats, which are most unsuitable for milling, and we think it would be very unfortunate if the tendency to grow oats for the sake of high yields only, is continued.'

When the Scottish Plant-Breeding Station was established in 1921 it was decided that attempts should be made to procure:

1. Oat varieties having a high degree of resistance to 'lodging' and giving a high yield of well-filled, thin-husked grain.
2. Early-ripening oats adapted to high-lying and thin soils and giving higher yields of grain than the Potato and Sandy varieties.

Hybridization.—A certain amount of selection within named varieties was made during the first few years, but the types selected were in no way outstanding, being in most instances similar to the varieties from which they were originally taken or to well-known standard varieties. As the possibilities of selection alone appear to be largely exhausted, hybridization has been practised on an extensive scale. Although the work has been directed more towards synthesis than analysis, genetical analyses have been made of several characters, chief attention being given to the mode of inheritance of grain (palea) colour and of striped leaves.

The writer has found more difficulty in securing artificial hybrids of oats than those of barley or wheat. The oat floret appears to be very easily damaged when the inner palea is bent outwards. Opening the florets in this way for the purpose of emasculation was first tried, but with little success. More success was obtained by cutting away most of the inner palea and the upper half of the outer one of each floret selected for emasculation. When these portions are cut away the exposed stigma may be protected against chance pollination by placing a small specially prepared paper bag over the emasculated floret. The bags are easily removed when access to the emasculated florets is required, and pollen

can be applied without any further mutilation of the florets, as may readily happen if the paleae have to be opened a second time. These bags do not adversely affect the setting of seed. It has frequently been observed that if artificial pollinations are made in dull or showery weather the number of pollinated florets which set seed is very small, whereas if the pollinations are made in dry, warm, and sunny weather, more seed results.

In sowing the F_1 seeds each grain is sown in a small pot in a greenhouse, a plan that helps to ensure accuracy of origin and often saves loss of material from damage by vermin. It is advantageous not to grow the seedlings in pots throughout the whole growing season, but to transplant them to fertile soil when they are about 6–12 inches high. If the seedlings are carefully transplanted their growth will not be checked. This is important, because it is an undoubted advantage to have a large F_2 generation; when a plant is well grown, considerably over 1,000 grains may be obtained from it (in one instance a F_1 plant has produced over 1,500 grains). The grains from the plants of the first and succeeding generations are sown in the field, single seeds being placed in dibble holes at 2-inch intervals in rows 9 inches apart.

Heredity.—Detailed observations on the inheritance of grain colour and of striped leaves have already been published elsewhere: they confirm the genetic schemes worked out by Nilsson-Ehle and others. With regard to grain-colour inheritance, the varieties Black Bell, Black Mogul, and Black Tartarian have been observed to possess one factor for black grain; the varieties Myrtle and Black Mesdag one factor for black grain and one factor for grey grain. The Swedish variety Orion has been frequently used as a parent with white-grained varieties, and it has been shown to have two factors for black grain and one for grey grain. The F_2 progenies of the crosses (white-grained × black-grained) in which the black-grained parent possessed only one factor for coloured grain, were easily classified into two groups, viz. black and white. In these crosses (white-grained × black-grained) in which the black-grained parent had either one or two factors for black grain and one for grey grain, the progeny plants were much more difficult to classify in the F_2 generation. The grains ranged in colour from a deep black through reds and greys to the white of the white-grained parent; and there were many intermediate types between the slightly grey and the black grain that could not be classified accurately. Frequently an F_3 generation had to be grown in order to ascertain the genetic constitution of the F_2 parent plants.

Observations have been made for several years on the inheritance of striped leaves in oats. The striped-leaved plants were derived from two plants showing yellowish stripes on the leaves, and they occurred in a hybrid progeny, Sandy × Record. Six generations have been grown, and the later progenies are still very variable. Striped-leaved plants have produced a small proportion of plants with apparently normal green leaves, but no plants entirely devoid of green colour have been observed in any progeny. Frequently, however, seedling plants that were markedly deficient in green colour died at an early stage.

Striped-leaved plants have been used both as male and as female parents. When a striped plant was the male parent no striped-leaved

plants appeared in any of the progenies. In reciprocal crosses, however, the F_1 plants had striped leaves, as had also many of the plants in succeeding generations. Generally, the proportion of plants in different progenies having green leaves was small. It was found that striped leaves in oats were inherited through the maternal parent only, thus confirming the results obtained by Åkerman.

Breeding for resistance to lodging.—The aim of this work has been to unite resistance to lodging with ability to give a high yield of well-filled, thin-husked grain. It may be observed that the stems of lodged oats are not always bent or broken, but may be tilted over from their upright position at the surface of the ground through inability of the roots to maintain the mature plants in an erect position. In selecting hybrid plants for resistance to lodging, the relative length of the straw and the type of roots developed were taken into consideration, and when harvesting individual plants preference was given to plants having roots that were strong and well spread out.

Many varieties of oats have been crossed to ascertain the combinations which give the best upstanding straw. The most promising material for Scottish conditions has been obtained from certain crosses with the Potato oat. The Potato variety is not noted for its resistance to lodging, but in several of its hybrid progenies there appeared types which showed 'transgression' towards shorter straw and possessed strong, well-developed roots. Some of these also had well-furnished panicles bearing spikelets with two, and occasionally three, grains rather larger than those of the Potato variety. These relatively short-straw plants have, under suitable conditions, produced a high yield of grain. One variety of this type has been reported as yielding over eleven quarters per acre from eight acres. On fertile soils where lodging is prevalent, there is generally an ample supply of moisture, and consequently the straw tends to be too long to carry the heavy panicles. It is for soils such as these that the relatively short-straw varieties have been developed.

In several of the selections from Potato and from Sandy crosses, 'transgression' towards a type ripening later than either parent has been observed. However, in the progeny of the hybrid, Potato × Record, transgressive segregation towards an earlier-ripening type has been observed, and this has been accompanied by a good quality of upstanding straw and a high grain-yielding capacity. Another 'transgression' type which also occurred in some of these crosses was towards extreme length of straw. In one season the tallest plants varied in height from 6 feet to over 7 feet, in comparison with a height of about 5 feet in the parents. Subsequent breeding has shown that these long-straw plants are distinct genetic types.

Breeding for early maturity.—To obtain early-ripening varieties, adapted to upland districts of Scotland, several varieties, including Potato and Sandy, have been successfully cross-pollinated with very early-ripening varieties like Black Mesdag, Eighty Day, Sixty Day, and Orion. The F_1 plants seemed to be intermediate in period of ripening, but there was much variation in the F_2 generations. Between the two extremes of early-ripening and late-ripening types there was a range of plants which were

difficult to group. Although the hybrid progenies from Black Mesdag, Eighty Day, and Sixty Day contained some very early-ripening plants, all of them had very weak straw, and the grain was low in yield and not well filled. None of the early-ripening plants from any of these crosses was considered worthy of propagation, but rather more promising material was found among the Orion crosses. The F_2 plants from the latter were difficult to separate into definite groups in regard to period of maturity. None ripened any earlier than the parent variety Orion, but in several of the Sandy × Orion series, plants decidedly later in ripening than Sandy —the later-ripening parent—were observed. These were probably 'transgression' types, as the late-maturing character prevailed. The grain in many of the Orion crosses was well filled and was much more attractive than that of any of the Black Mesdag, Eighty Day, and Sixty Day crosses.

Certain very early-ripening varieties from Australia have been crossed with a few varieties commonly grown in Scotland, and some promising material has been obtained from the hybrid progenies.

Shedding of the grain.—In exposed situations loss is occasionally experienced through the plants shedding their grain before they are harvested, and the old-established variety Sandy is one of the most resistant in this respect. Its yield of grain is generally low, and improved varieties possessing some of its best characters are desired. Good results have been obtained from a progeny of Sandy × Leader, and one selection from this cross, now named Bell, has given encouraging results in different districts as widely separated as Orkney in the north, Selkirkshire in the south-east, and Argyllshire in the west of Scotland.

Selection.—In cereal-breeding experiments two different methods of selection may be followed in working with the hybrid progenies succeeding the first generation. In one method the material is massed without any selections being made until about the sixth generation, when a large proportion of the individuals of the population will be breeding true in many characters. In the other method, single plants are chosen in each generation from the F_2 onwards until the selected types are breeding true for the essential characters. The latter method has been followed in the oat-breeding work at this Station.

Comparison of new selections.—When promising hybrid selections appear to be fixed, further comparisons are made in small plots during the early stages of multiplication. These trials allow of further eliminations being made, and after the first two years of multiplication, the more promising selections are sown in small replicated field trial-plots for comparison with standard varieties, such as Potato, Sandy, and Victory; and also with other named varieties as occasion demands, in order to obtain information regarding their grain-yielding capacity. During the last few years thirty varieties (four plots of each) have been compared each season. The yield of grain in a new variety is important, but, of course, other characters such as quality of grain and straw, period of maturity, and freedom from various diseases must also be taken into account when making comparisons.

In addition to the trials carried out at the Plant-Breeding Station, oat trials are arranged in co-operation with the agricultural colleges in Scot-

land. These permit of new varieties being tested under a wide range of conditions, and have been helpful in providing information on the merits of new selections. The Department of Agriculture for Scotland has a scheme in operation for testing and registering new varieties of cereals, and all the promising new selections of oats raised at the Scottish Plant-Breeding Station are submitted for inclusion in the Department's registration trials. The results of these trials assist breeders to ascertain the utility of new selections, and also provide independent information for farmers concerning the merits of new varieties.

New Varieties

Three varieties raised at this Station have been registered by the Department of Agriculture for Scotland under the Cereals Registration Scheme. They are named Elder, Bell, and Early Miller, and were registered respectively in November 1930, January 1932, and January 1934. They have been tested only as spring-sown varieties. Extracts from the Certificates of Registration and a few general notes regarding these varieties follow:

Elder.—The special qualities of this oat are: '(1) its good tillering habit; (2) its special capacity to withstand lodging; (3) its well-furnished head of corn; (4) its good yield on fertile soils; (5) its attractive sample of grain, and (6) its suitability as a lea oat.' The parentage of this oat is Castleton Potato × Beseler's Prolific. It was put into commerce in 1931.

In trials carried out by the North of Scotland College of Agriculture at Craibstone Experimental Farm, Aberdeen, it was reported that Elder withstood lodging better than any other variety, and that it gave a yield of 34·2 cwt. per acre, as compared with a yield of 34·5 cwt. from Victory. In trials at Boghall Experimental Farm, Edinburgh and East of Scotland College of Agriculture, Elder gave a yield of 28 cwt. of grain per acre, as compared with 32 cwt. of grain per acre from Victory, the experimental error being estimated at about 5 per cent. It was specially noted in the report for its stiff straw; it was the stiffest-strawed variety of six in the trial, which included Victory, Sovereign, Echo, Star, and Silver. In a field trial near Rothes in Morayshire, Elder gave a yield of grain at the rate of 36 cwt. per acre in comparison with 30 cwt. per acre from Victory, and the crop stood satisfactorily until it was cut. At Corstorphine a nine-acre field of Elder oats gave a yield of grain of about 30 cwt. per acre.

Bell.—'An early variety having many of the characters of Sandy Oat; of good tillering habit; very early in ear, maturing slowly; earlier in ripening than Sandy or Potato oat; having a moderately good yield of medium grain, faintly pink tinged; not liable to shed; having a large yield of good straw not so liable to lodge as Sandy; suitable for poorer soils and late districts.'

The parentage of this oat is Sandy × Leader. It was put into commerce in 1932, and very favourable reports regarding it have been received from growers in upland districts in various parts of Scotland.

The Bell oat was selected as a possible substitute for the old-established variety Sandy. At Corstorphine it has given higher, but not significantly

higher yields of grain than Sandy. The Agricultural Organizer for Caithness reported on a trial there that 'this variety compares favourably with Potato, Sandy, Golden Rain, and Plentiful, grown in the same field, and the yield of 20 cwt. 70 lb. per acre is considered very satisfactory in this district'. Captain Thomas Elliot, Thirlestane, Lauder, Selkirkshire, has reported as follows: 'I sowed these oats after turnips on a poorish field, 880 feet above sea-level, at the rate of 4 bushels per acre. They grew a good crop, tall and all perfectly standing, and when cut were dead ripe. They ripened at least a week earlier than the remainder of the field, which was sown with Yielder. The yield of dressed grain was 20·8 cwt. per acre, and the natural weight of these oats was 45 lb. per bushel.'

Early Miller.—'A white-grained oat which is in general character intermediate between its parents Potato and Record; an early-ripening variety suitable for general cultivation and high-yielding on fertile soils. The grain is short and plump, well filled and of an attractive colour; not thick in the husk, but gives a high bushel weight, and shows promise of being a high-class milling oat. The straw is of good fodder quality and of medium length, and possesses a high degree of resistance to lodging.'

This variety was put into commerce in 1934, and there was a very keen demand for the seed. Favourable reports on it have been received from trials carried out in various parts of the country. At Corstorphine a yield of grain of 30 cwt. per acre was obtained, and this was equal to the yield from Victory. In a trial in Kincardineshire conducted by the North of Scotland College of Agriculture, a yield of grain at the rate of over 40 cwt. per acre was reported. In several other trials yields of over 30 cwt. of grain per acre were obtained. Favourable reports on the milling quality of the grain of this variety have been received from two oatmeal millers. One report states: 'From a milling point of view the oats are very promising, as they do not appear to be so fibrous as many varieties grown at present, which make oatmeal of a poorer quality than the old Potato and other thin-skinned varieties.'

In Table 1 figures relating to the 1932 crops at this Station are quoted showing the weight in grams of 1,000 grains, the percentage of kernel and the yield of grain in the three new varieties, Elder, Bell, and Early Miller, in comparison with those of Potato, Record, and Sandy. It will be seen that in all of the three new varieties the grains are of medium size and contain a higher percentage of kernel than the grains of Record.

In Table 2 are shown the results of chemical analyses made by Dr. Alexander Lauder, Edinburgh and East of Scotland College of Agriculture, on samples of the grain of five different varieties, including Elder, Bell, and Early Miller. Analyses of the grain of Potato, 1932 and 1933 crops, are given for comparison. The grains of the varieties Potato and Sandy have always been considered to be of high feeding-quality. On the whole, however, there does not seem to be much difference in the feeding-value of the five varieties tested.

An important feature brought out by the analyses is that Early Miller shows the highest percentage of oil. This is an additional point in favour of this new oat. There appear to be considerable differences in the moisture-content of the 1932 grain as compared with that of 1933, but

these differences do not seriously affect the percentages of the other constituents mentioned in the analyses.

TABLE 1. *Comparison of New Varieties with Established Varieties*

Name of variety	*Weight of 1,000 grains (grams)*	*Percentage kernel*	*Yield of grain when Victory = 100*	*Yields compared statistically with*		
				Victory	*Potato*	*Sandy*
Elder .	36·37	74·9	90·0	N.S.*	S.H.*	S.H.*
Bell . .	34·71	77·9	78·0	S.L.	N.S.	N.S.
Early Miller	37·64	76·2	96·0	N.S.	S.H.	S.H.
Record .	42·40	73·6	96·0	N.S.	S.H.	S.H
Potato .	30·28	77·3	76·5	S.L.	..	N.S.
Sandy .	26·71	77·8	71·0	S.L.	N.S.	..

S.H. = significantly higher yield; N.S. = no significant difference; S.L. = significantly lower yield.

Standard Error = 3·8 per cent. of mean yield of grain of Victory. A difference of more than three times the standard error is regarded as significant.

* Elder suffered more than the others from lack of moisture.

TABLE 2. *Chemical Analyses of Samples of Grain of Five Different Varieties of Oats*

Variety	*1932 Crops*				*1933 Crops*	
	Elder	*Bell*	*Potato*	*Sandy*	*Potato*	*Early Miller*
Crude protein (albuminoids) . .	9·12	10·91	11·54	11·19	10·87	9·68
Oil (ether extract) . .	4·36	4·37	3·46	4·29	4·04	5·40
Crude fibre . . .	8·72	8·23	6·83	9·62	9·34	10·92
Soluble carbohydrates .	60·26	59·92	62·32	57·48	62·48	62·90
Mineral matter . .	3·14	2·51	2·50	3·02	2·59	2·59
Moisture . . .	14·40	14·06	13·35	14·40	10·68	8·51
	100·00	100·00	100·00	100·00	100·00	100·00

Summary

The objects of the oat-breeding work and the methods followed at the Scottish Plant-Breeding Station are indicated.

Hybridization has been practised on an extensive scale and an outline is given of some of the results that have been obtained. Reference is made to the differences in the genetical constitution of several black-grained varieties in respect of grain colour, and to the mode of inheritance of striped leaves in oats.

The procedure followed in the testing of new varieties raised at the Station is described.

Certificates of registration have been granted by the Department of Agriculture for Scotland in respect of three new varieties of oats, viz. Elder, Bell, and Early Miller, raised at the Scottish Plant-Breeding Station. Descriptive notes are given regarding these varieties, which have been put into commerce by the Scottish Society for Research in Plant-Breeding.

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THE SOILS OF WALES[1]

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THE principality of Wales, lying to the west of England, has a total area, including Monmouthshire, of 8,015 square miles. Excluding urban and industrial areas, about 68 per cent. of its surface is under crops and grass.

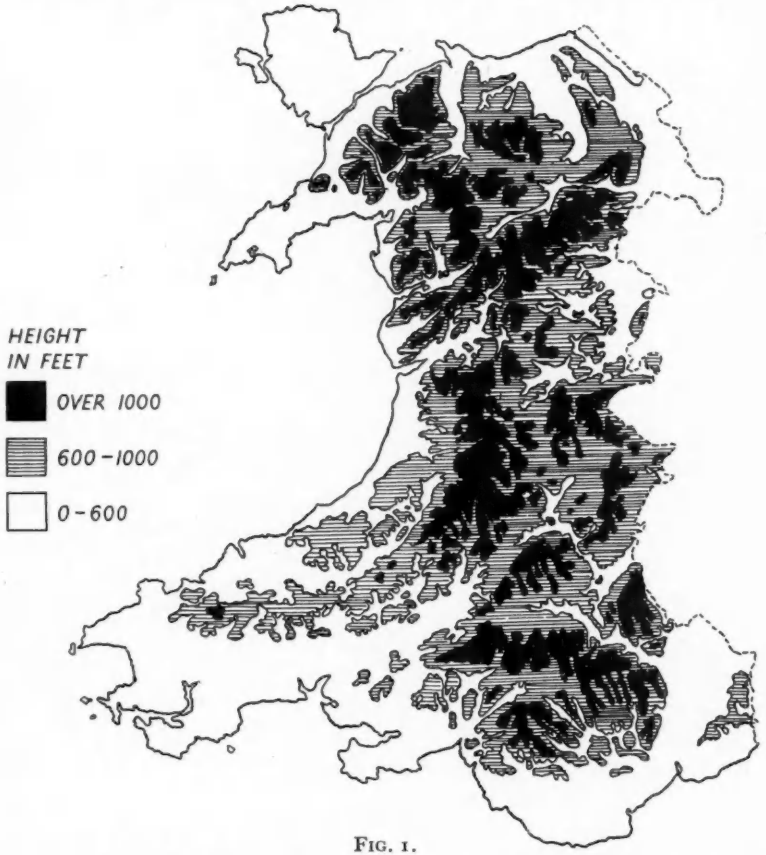

FIG. 1.

The uncultivated lands consist mainly of moor, heath, and mountain, the proportion varying from 6 per cent. in Flint to 57 per cent. in Merioneth.

Surface.—The character of the surface-relief is shown by the orographical map (Fig. 1). The highest point is reached in Yr Wyddfa

[1] Published on behalf of the Excursion Committee of the Third International Soil Congress, 1935.

(Snowdon), 3,571 ft. above sea-level, whilst several other peaks in Caernarvonshire are over 3,000 ft. in height. Apart from alluvial flats of comparatively small extent, there is little level ground. Over most of the country the surface-forms vary from the sharply-defined mountains and valleys or Eryri in Caernarvonshire to the rolling or undulating

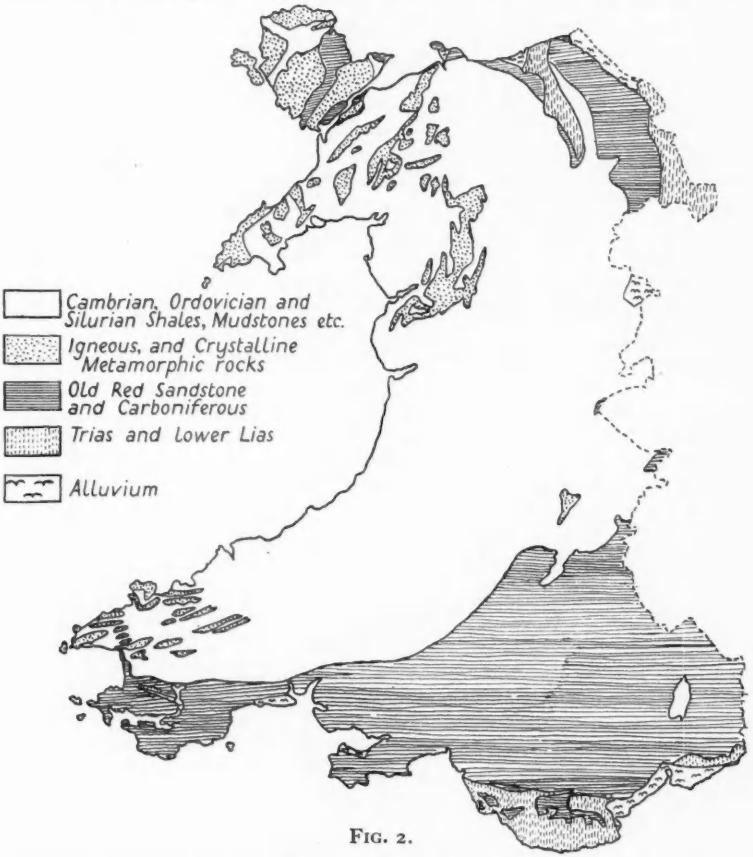
Cambrian, Ordovician and Silurian Shales, Mudstones etc.
Igneous, and Crystalline Metamorphic rocks
Old Red Sandstone and Carboniferous
Trias and Lower Lias
Alluvium

FIG. 2.

features of the lowlands. The upper limit of cultivation varies from about 600ft. in Caernarvonshire to about 1,200ft. in mid-Wales. Above the cultivated lands lie grass heath, moorland, and mountain, used for rough grazing by sheep. The area under forests is comparatively small, but planting is being carried out in certain districts by the Forestry Commission.

Geology.—The geological character of Wales is seen from the generalized map in Fig. 2. Pre-Cambrian rocks, mainly schistose and gneissose, occur in Anglesey, west Caernarvonshire, and Pembrokeshire. The greater part of the area of Wales is occupied by Cambrian, Ordovician,

and Silurian rocks. Apart from igneous rocks occurring in the Ordovician of Caernarvonshire and Merionethshire, these formations consist principally of a succession of non-calcareous sediments, sometimes exhibiting a considerable degree of metamorphism, as in the Cambrian slates, but always considerably altered from their original character. Soils derived from Lower Palaeozoic Sediments have thus, to a considerable degree, the character of soils of primary weathering, and more closely resemble soils derived from crystalline rocks than soils derived from sediments, such as the Triassic Marls, in which the original clay complex has persisted.

Old Red Sandstone occurs in a small outcrop in North Wales but reaches a considerable development in South Wales, particularly in Brecon and Monmouth. As soil-forming materials, the rocks of this formation occupy a position mid-way between the highly altered Lower Palaeozoic Sediments and the comparatively unaltered sediments of the Trias and later formations. They form a succession of marls and sandstones, often micaceous, distinguished by their warm red colours, which persist in the derived soils.

The Carboniferous Limestone occurs both in North and South Wales. It is generally formed of hard rocks whose derived soils vary according to situation and depth. The Millstone Grit and Coal Measures form a variable series of sediments, some of which (e.g. the Pennant Grits) show resemblances to the altered sediments of Lower Palaeozoic age, whilst others resemble the Triassic and later sediments.

The Trias occupies a comparatively small area in North Wales and South Wales. There are, however, along the north coast, considerable spreads of red boulder clay which is probably, in the main, Keuper Marl material. Triassic Red and Green Marls are found in Glamorgan, where Rhaetic Limestone also occurs. The Lower Lias Limestone of Glamorgan, from the soil-forming standpoint, resembles closely the Rhaetic, and gives rise to soils which appear to be related to the rendzinas.

Among recent deposits are estuarine and fluviatile alluvia, blown sands, and peat.

There are in all parts of Wales evidences of glacial action, but the drifts are, for the most part, local material either in the form of boulder clay or sands and gravels. The deepest drifts occur along the north-eastern border and along the north coast.

Climate.—The climate of Wales is typically maritime, with mild winters and cool summers. This character is most pronounced in the coastal districts, particularly in the west, where severe frosts and snow are comparatively rare. More rigorous conditions prevail in the upland regions, and the higher mountains are frequently capped with snow during the winter and early spring months. The rainfall is closely related to the surface-relief, as may be seen by comparing Figs. 1 and 3. The highest mean annual rainfall is about 200 in., near the peak of Snowdon. A considerable area in North Wales receives a rainfall of over 100 in. per annum.

Meteorological statistics for representative Welsh stations are given in Table 1.

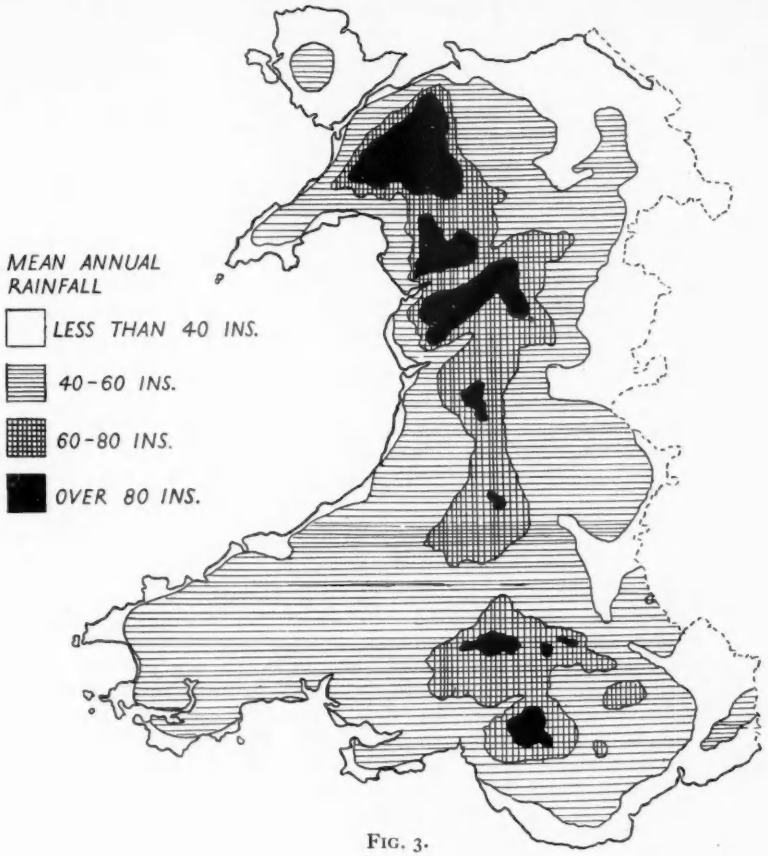

FIG. 3.

TABLE 1. *Meteorological Data for Typical Welsh Stations*

Station	*Altitude (feet)*	*Mean temperature, °F.*			*Mean Annual Rainfall (inches)*
		January	*July*	*Year*	
Chester	22	39·9	60·7	49·6	24·3
Rhyl	30	40·4	59·4	49·1	25·8
Llandudno	71	41·4	60·1	49·9	30·0
Holyhead	15	41·8	58·5	49·5	34·9
Aberdovey	22	41·4	60·9	50·8	36·0
St. Ann's Head	149	42·7	58·4	49·9	35·2
Cardiff	202	38·9	60·5	49·1	41·4
Bettws-y-Coed	148	39·8	58·8	48·4	48·7
Gwernyfed, Brecon	374	37·6	59·4	47·7	31·5
Llangamarch, Brecon	550	38·0	58·6	47·1	48·0

Typically, the Welsh climate is distinguished by an equable temperature, abundant and well-distributed rainfall, and a generally humid atmosphere. In the lowlands, frost occurs only occasionally and it is exceptional for the temperature to remain below freezing-point throughout the day. The frost-free period is practically co-extensive with the year so far as the pedogenic processes are concerned.

The husbandry of Wales is mainly of the grassland type and the equable climate ensures a long growing-season and, with good management, a large yield of grass.

The climate of the uplands is more rigorous, but the proximity of the sea and the prevalence of mild south-westerly winds mitigate its severity. Although the rainfall is considerably higher in the uplands than in the lowlands, the shallow character of the soils intensifies the effects of drought, which actually becomes a limiting factor in the growth of grass and determines a heathy type of vegetation.

CLASSIFICATION OF WELSH SOILS

For the purpose of soil survey it has been found convenient to group the soils of Wales into *suites*, each suite consisting of the soils formed from a definite class of parent material, e.g. the Bangor suite derived from acid igneous rocks and their associated drifts. The suites are further subdivided into *series*, each series representing a certain type of profile development. For details of this classification the reader is referred to publications in connexion with the Soil Survey of Wales.

For the present account of the soils of Wales, however, it seems better to adopt a classification which can be directly correlated with a world system, and in which the differences introduced by parent material appear as subdivisions. The following classification is suggested:

A. *Soils with Free Drainage*

1. *Podsols*
   (*a*) Developed profiles
   (*b*) Eroded or truncated profiles
2. *Skeletal and undeveloped soils*
3. *Brown earths*
   (*a*) Shallow
   (*b*) Deep
4. *Limestone soils*
   (*a*) Rendzinas
   (*b*) Brown limestone soils
5. *Dune soils*

B. *Soils with Impeded Drainage*

1. *Permanent ground-water soils*
2. *Seasonal ground-water soils*
3. *Peats*
   (*a*) Bog peats
   (*b*) Mountain peats

We shall now proceed to a description of the individual classes of soils.

A. *Soils with free drainage*

1. *Podsols*

From the temperate and humid character of the Welsh climate and from the fact that the parent materials are generally non-calcareous, a podsolic type of profile might be expected where conditions favour mature development. Actually, well-developed podsols are by no means common. This may be expected from the following circumstances:

1. Although calcareous parent materials are not widespread in Wales, yet the soils derived from crystalline rocks and from the Lower Palaeozoic Sediments offer considerable resistance to podsolization. Quartzites and quartzose sands are of comparatively infrequent occurrence. Dune sands of the coastal regions are not sufficiently stable for the development of mature profiles.

2. The primitive vegetation of Wales up to about 1,700 ft. was deciduous forest and swamp. There is no original coniferous forest. Most of the soils showing podsolization at the present day are developed under heath or grass heath secondary to the original deciduous forest.

3. A considerable proportion of the area of the country shows impeded drainage. For example, in Anglesey, probably two-thirds of the area is of this character. Where such conditions occur, a different type of profile develops, namely, that of ground-water or meadow soils, or, in extreme cases, peats.

4. There is evidence that considerable erosion has taken place in past centuries, possibly in the interval between deforestation and the establishment of grassland and heath. Large areas in the uplands show profiles which suggest truncation, for the surface soil has the character of B horizon material. Indeed it is possible that many of the podsols now encountered are actually secondary, having been developed by the podsolization of an original B horizon laid bare by erosion.

5. About two-thirds of the area of the country is in crops and grass, and of this the greater part has at some time come under cultivation, with the consequence that the original horizons have been obliterated to the depth of tillage. Moreover, the maintenance of land in cultivation, involving the addition of lime and other mineral dressings, tends to check the podsolization process.

(*a*) *Developed profiles.*—In spite of these obstacles to the development of mature podsols, evidences of podsolization are readily obtainable. Shallow podsolic profiles can generally be found under heath vegetation. In some cases, the presence of peaty organic matter obscures the bleaching of the A horizon, which only becomes evident after peroxide treatment. In other cases, the B horizon, if it can be said to exist, occurs in the interstices of the underlying rock on which the A horizon rests directly. We shall now describe some typical podsol profiles.

The first profile is developed in quartzose Old Red Sandstone conglomerate at Cefn-y-Bryn, West Glamorgan, under a grass-heath vegetation, consisting of *Ulex Gallii*, *Ulex europaeus*, and fescues. The altitude is 300 ft. and the mean annual rainfall 40 in. The description (D. O. Hughes and Brynmor Jones) is as follows:

A_0. 0–4 in. Fibrous peaty layer.
A_1. 4–7 in. Greyish fine sand.
B. 7–12 in. Reddish-brown sandy loam.
B–C. 14–16 in. Yellowish-brown sandy loam over rock.

The analytical figures are as follows:

	A_1	B	B–C	
Organic carbon	1·6	2·1	0·5	per cent.
pH	4·64	4·68	5·52	
Clay fraction: SiO_2/Al_2O_3 . .	3·70	2·44	2·80	
,, SiO_2/R_2O_3 . .	3·33	1·67	2·03	
,, Al_2O_3/Fe_2O_3 . .	9·00	2·17	2·63	

The figures show a slight accumulation of humus in the B horizon, a feature not generally noticeable in Welsh podsols. The eluviation of the sesquioxides affects principally the ferric oxide, as is shown by the trend of the Al_2O_3/R_2O_3 ratio.

Quartzose parent materials are comparatively uncommon in Wales. Apart from the Old Red Sandstone conglomerate, and the Anglesey quartzites, the only highly quartzose parent materials are found in the Millstone Grit of North Wales. In the Wrexham district, podsols can be observed under heather vegetation on the Millstone Grit uplands. In these, as in the Cefn-y-Bryn profile, the B horizon rests directly on the parent rock, and in some cases sinks within it, as in certain profiles developed on quartzite near Holyhead, where the bleaching affects the surface of the rock.

Most of the Welsh podsols are developed in non-calcareous sedimentary rocks of Cambrian, Ordovician, and Silurian age. They are generally somewhat shallow and stony or brashy. Humus B horizons are almost invariably lacking. They occur generally above the limit of cultivation under a grass heath or heath vegetation. A typical example occurs at Aber, Caernarvonshire. It is developed on Ordovician Grit under a vegetation of *Calluna vulgaris*, *Vaccinium Myrtillus*, fescues, and lichens. The altitude is 900 ft. and the mean annual rainfall about 60 in. The description is as follows:

A_0. 0–5 in. Peaty layer.
A_1. 5–8 in. Greyish silt loam.
B_1. 8–14 in. Reddish-brown loam.
B_2. 14–20 in. Light brown shaly loam.
B_3. 20–26 in. Light brown very shaly loam on rock.

The analytical data are as follows:

	A_0	A_1	B_1	B_2	B_3	
Organic carbon . . .	13·8	6·2	4·7	3·5	3·6	per cent.
pH	3·64	4·1	4·68	4·70	4·82	
Clay fraction: SiO_2/Al_2O_3 .	4·40	3·84	1·90	2·09	1·56	
,, SiO_2/R_2O_3 .	3·56	2·75	1·31	1·39	1·17	
,, Al_2O_3/Fe_2O_3 .	4·24	2·52	2·22	1·99	3·00	

There is no evidence of a humus B horizon, but the content of organic carbon remains fairly high down to the rock. The decrease of the SiO_2/R_2O_3 ratio down to the rock suggests that the B horizon

extends down to it. The maximum accumulation of ferric oxide is in the B_2 horizon.

Deep podsol profiles can only occur in drift, since sedentary soils are generally shallow. In the lowlands where drifts having free drainage occur, they are generally under cultivation. The following example indicates the type of podsol profile which can occur in drift. It is found near Pentre Voelas, Denbighshire, developed in shaly drift under a vegetation of *Nardus stricta*, *Galium saxatile*, *Hypnum*, *Polytrichum*, and *Holcus mollis*. The altitude is 1,358 ft. and the mean annual rainfall about 55 in. The following is the description:

A_0. 0–6 in. Dark brown to black peat, mainly amorphous but fibrous at the surface and occasionally below.

A_1. 6–10 in. Dull grey, heavy silt loam.

B_1. 10–22 in. Reddish-brown or, in places, yellowish-brown, heavy silt loam with angular stones. Slight ortstein development at top.

B_2–C_1. 22–34 in. Greyish-brown, gritty and stony, heavy silt loam.

C. 34 in. Light-grey, compacted, heavy silt loam with numerous stones.

The analytical data are as follows:

		A_0	A_1	B_1	B_2–C	C
Organic carbon		..	1·96	4·48	0·58	0·32 per cent.
Clay		..	19·9	17·9	13·7	17·4
pH		3·86	4·2	4·4	4·6	4·8
Clay fraction:	SiO_2/Al_2O_3	..	2·51	2·10	2·44	2·32
,,	SiO_2/R_2O_3	..	2·40	1·60	2·00	1·98
,,	Al_2O_3/Fe_2O_3	..	21·66	3·15	4·47	5·74

The field characters of this profile and the natural vegetation suggest a certain degree of drainage impedance. Such impedance may possibly have developed after an earlier phase of podsolization under freely-drained heath condition.

(*b*) *Truncated profiles.*—In many parts of the uplands of Wales lying immediately above the cultivation limit may be seen shallow reddish-brown soils under grass heath, often with bracken and gorse. Such a profile occurs in Ordovician Shale at Aber, near Bangor, under a vegetation of grasses and bracken. The altitude is about 800 ft., and the mean annual rainfall about 60 in. It occurs at a slightly lower level than the podsol described above. The description is as follows:

0–3 in. Turfy layer.
3–6 in. Dark-brown turfy loam.
6–9 in. Brown loam.
9–12 in. Light-brown light loam.
12–15 in. Reddish-brown shaly loam on rock.

The analytical data are as follows:

		0–3 in.	*3–6 in.*	*6–9 in.*	*9–12 in.*	*12–15 in.*
Organic carbon		15·9	8·1		5·4	3·4 per cent.
pH		4·20	4·42	4·58	4·78	4·82
Clay fraction:	SiO_2/Al_2O_3	2·17	2·25	2·17	1·95	2·12
,,	SiO_2/R_2O_3	1·63	1·69	1·62	1·48	1·50
,,	Al_2O_3/Fe_2O_3	3·02	3·02	2·95	3·13	2·42

The appearance of the profile suggests B-horizon material, and this is supported by the data for the composition of the clay fraction. Such profiles are of widespread occurrence, and it appears reasonable to conclude that the corresponding A horizon in such cases has been removed by erosion in past centuries, possibly consequent on the removal of the primitive deciduous forest.

It may be added that truncated podsols are not confined to the uplands. In many lowland situations with strong surface-relief, soils occur which are characterized by low silica-sesquioxide ratios, and an inversion of the usual order whereby the silica-sesquioxide ratio of the clay decreases from the surface. It can only be inferred that this corresponds with a transition from B- to C-horizon material.

In some profiles, although no bleaching is perceptible, a study of the clay fraction reveals a certain amount of sesquioxide eluviation from the surface horizon. This may be expected to become accentuated with further degeneration and result in the development of a definite podsol profile. Some of the podsols actually encountered are probably of this secondary character.

2. *Skeletal soils*

Podsols, either developed or truncated, are generally encountered under conditions of free drainage in a belt above the limit of cultivation. At higher altitudes mountain soils occur in which the profile consists of a turfy or peaty layer over a thin brash layer passing quickly to rock. There is no marked development of an A or B horizon, and the whole profile consists of material which has progressed but slightly beyond the stage of physical disintegration. No definite altitude can be assigned for the transition from podsols to skeletal soils, but about 1,800 to 2,000 ft. may be provisionally suggested. Skeletal soils may also occur at lower elevations. Many of the isolated rocky outcrops in Anglesey carry such soils, which may represent extreme cases of truncation down to the C horizon.

With the skeletal soils one may venture to group certain soils which appear to be pedologically undeveloped, but which, from the agricultural standpoint, are definitely soils. Such soils occur associated with Old Red Sandstone and Triassic Marls. Apart from the addition of humus and structural modification, they scarcely differ from the parent geological formation, and exhibit no mechanical or chemical eluviation. Soils of this class may be encountered in many parts of the world associated with soft argillaceous sedimentary rocks. They reflect the character of the geological parent material, rather than the operation of contemporary pedogenic processes. Many alluvial soils can be placed in this class; but where there is drainage impedance, or where a water-table exists near the surface, they are more appropriately assigned to the group of soils with impeded drainage.

3. *Brown earths*

The soils placed in this group are freely leached soils in which translocation of sesquioxides has not occurred to an extent sufficient to produce

a bleached A horizon and a horizon of sesquioxide accumulation. In the shallower profiles a certain eluviation can be demonstrated by analysis of the clay fractions, and there is a gradual transition to podsol profiles, either of the developed or the eroded types.

In assigning the soils to be described in this section to the brown earths, the writer is aware that such an assignment is open to criticism and calls for some explanation. The term brown earth is, of course, used in somewhat different senses by different writers. If, however, the common characteristics are considered, it will be seen that they are the following: (*a*) free drainage; (*b*) complete leaching out of calcium carbonate from the soil profile; (*c*) absence of a peaty humus layer; (*d*) no visible segregation of sesquioxides resulting in bleaching in the A horizon and sesquioxide accumulation in the B horizon; (*e*) brownish colours suggesting the presence of free ferric oxide or one of its hydrates.

The soils of Wales which have been provisionally assigned to the brown earths possess all the characteristics enumerated above. They may be assigned to a sub-group of the brown earths on account of their high content of organic matter, which results from their having been long under a system of utilization involving long periods under artificial grass. To what extent the slight sesquioxide eluviation revealed by analysis separates them from other brown earths cannot be stated since corresponding figures for typical brown earths in other parts of the world are not available. Further, although these soils are all freely drained, it is not to be denied that over a considerable period of the year their moisture-content is very high, so that anaerobic conditions must prevail.

(*a*) *Shallow profiles.*—These are sedentary soils generally under crops or artificial grassland. Any slight bleaching of the surface horizon which may have been present under virgin conditions has been obliterated by cultivation. The surface horizon is generally dark in colour owing to the presence of humus. The colour of the subsoil generally differs from that of the soil only by being somewhat lighter, owing to the smaller proportion of organic matter present.

The following profile is typical of the shallow brown earths developed from crystalline rocks. It occurs near Beaumaris, Anglesey, over Pre-Cambrian schists under a mean annual rainfall of 36 in. at an altitude of 300 ft. It is at present in grassland.

A. 0–9 in. Chocolate-brown turfy loam.
B. 9–15 in. Light brown loam on rock.

The following analytical data were obtained:

		A	*B*
Organic carbon		4·25	2·10 per cent.
Clay		18·4	16·0
pH		5·2	5·8
Clay fraction:	SiO_2/Al_2O_3	2·64	2·19
,,	SiO_2/R_2O_3	2·01	1·71
,,	Al_2O_3/R_2O_3	3·19	3·56

A slight eluviation of sesquioxides is shown, but there is no suggestion of bleaching in the profile as seen in the field.

A similar profile is developed in Pre-Cambrian volcanic tuffs at Ffriddoedd, Bangor. The mean annual rainfall is 40 in., the altitude about 200 ft., and the vegetation old grass.

A. 0–6 in. Dark brown fibrous turfy loam.
B. 6–12 in. Dark brown very stony loam on rock.

The following analytical data were obtained:

		A	*B*
Organic carbon		8·42	7·38 per cent.
Clay		24·0	22·8
pH		5·3	5·5
Clay fraction:	SiO_2/Al_2O_3	2·71	2·11
,,	SiO_2/R_2O_3	2·11	1·69
,,	Al_2O_3/Fe_2O_3	4·03	4·00

The high and uniform content of organic carbon both in the A and B horizons is to be noticed. The figures for the clay fraction indicate podsolization, but the Al_2O_3/Fe_2O_3 ratio is unchanged and there is no visible leaching. It may be supposed that in the absence of calcareous dressings this soil will become more acid, will degenerate to heath, and develop a definite podsol profile.

(*b*) *Deeper profiles.*—These are developed in lowland situations in hillwash, boulder clay, or in glacial sands and gravels. They show considerably less evidence of eluviation than the shallower phases of the brown earths, and it is doubtful if they were ever podsolized to more than a slight degree.

A typical profile of this class occurs at Bryngof, Llanfairpwllgwyngyll., Anglesey. The altitude is 120 ft., the mean annual rainfall 36 in., and the parent material boulder clay derived from Pre-Cambrian (Gwna) schist. The vegetation is semi-permanent grassland. The description of the profile (D. O. Hughes and W. G. D. Walters) is as follows:

0–9 in. Dark brown stony loam.
9–15 in. Brown stony loam.
15–36 in. Reddish-brown stony loam.
36–48 in. Yellowish-brown stony loam.

The following data were obtained:

		0–9 in.	*9–15 in.*	*15–36 in.*	*36–48 in.*
Organic carbon		2·90	2·05	1·10	.. per cent.
Clay		18·7	20·0	16·9	..
pH		5·4	5·6	5·9	5·8
Clay fraction:	SiO_2/Al_2O_3	2·39	2·47	2·41	2·64
,,	SiO_2/R_2O_3	1·80	1·85	1·80	2·05
,,	Al_2O_3/Fe_2O_3	3·05	2·99	2·99	3·41

The data for the clay fraction show no downward movement of sesquioxides and the whole profile shows to a slight extent a B character, with a suggestion of C material in the lowest layer. It is possible that under the original vegetation, deciduous forest, a weakly developed A horizon was present. This has either been removed by erosion, or mixed with the top of the B horizon by cultivation.

Profiles similar to these, developed by primary weathering from

crystalline rocks or from altered sediments, are of frequent occurrence throughout Wales. The composition of the clay fraction is fairly constant down the profile. In some cases the silica-sesquioxide ratio of the clay approximates to 2·0. Such profiles may be considered to show the nearest approach to the ideal brown earth unaffected by silica-sesquioxide differentiation. In other cases, the silica-sesquioxide ratio may be considerably smaller and suggests B horizon material from which the corresponding A horizon has been removed by erosion. Generally speaking, the smoother the topography the more closely does the silica-sesquioxide ratio of the clay approach to 2·0.

In addition to soils of primary weathering, there are also corresponding soils of secondary weathering derived from sediments of Triassic and later age. These occur principally in South Wales but are also represented in the eastern part of North Wales. They show a more siliceous type of clay with comparatively little differentiation within the profile. For example, in a profile in Triassic Red Marl in Glamorganshire the silica-sesquioxide ratios of the clay in the two distinguishable horizons were 3·39 and 3·20 respectively.

4. *Limestone soils*

On account of their special character, it is convenient to consider soils derived from limestones as forming a single group. In this group we may distinguish (*a*) grey or brownish-grey soils of the rendzina class formed of residual material which still contains original calcium carbonate; and (*b*) residual soils from which calcium carbonate has been completely removed and in which the non-calcareous residue has undergone a type of decomposition resulting in a brownish or red soil.

(*a*) *Rendzinas.*—The soils assigned to this group are those derived from the soft limestones of the Lower Lias and Rhaetic of Glamorganshire. Soils of a rendzina character are occasionally found associated with Carboniferous Limestone, and further examination may reveal their more widespread occurrence, particularly among thin upland soils.

An example of a rendzina is furnished by a profile from Glamorgan, described by D. O. Hughes and J. O. Jones:

0–6 in. Greyish-brown stoneless clay loam.
6–15 in. Light yellowish-brown clay with occasional fragments of limestone.
15 in. Soft grey limestone.

The analytical data are:

	0–6 in.	*6–15 in.*	
Organic carbon	3·3	1·2	per cent.
Clay	39·5	44·0	,,
$CaCO_3$	2·7	17·7	,,
Clay fraction: SiO_2/Al_2O_3	4·50	4·29	
,, SiO_2/R_2O_3	3·56	3·47	
,, Al_2O_3/Fe_2O_3	3·79	4·00	

Whilst these soils differ in some respects from continental rendzinas, their general character appears to warrant their inclusion in the group, probably as a sub-class.

A shallow profile near Penmon, Anglesey, over Carboniferous Limestone, for which, however, no analytical data are available, appears to resemble more closely some of the continental rendzinas. It consists of:

0–5 in. Black humus loam with angular limestone fragments.
5 in. Shattered limestone rock.

(*b*) *Red and brown limestone soils.*—These soils are commonly associated with Carboniferous Limestone. They are generally base-unsaturated, and such carbonate as they contain is generally in the form of hard fragments. The colours are warm brown, brownish-red, and even bright terra-cotta red. A typical profile is found near Bridgend, Glamorgan, under grass vegetation at 300 ft.:

0–9 in. Ruddy reddish-brown silty loam.
9–15 in. Brown silty loam with limestone fragments.
15 in. Hard limestone.

The composition of the clay fraction is as follows:

	0–9 in.	*9–15 in.*
SiO_2/Al_2O_3	2·50	2·76
SiO_2/R_2O_3	2·07	2·17
Al_2O_3/Fe_2O_3	4·22	3·71

Other profiles of this type show similar analytical data for the clay fraction, the SiO_2/R_2O_3 ratio tending to approximate to 2·0.

A profile at Bodeilio, Anglesey, in Carboniferous Limestone drift, presents an interesting example of de-silicification consequent on removal of carbonates. Three horizons were examined, namely 0–15 in., 15–30 in., and 30 in., respectively. Carbonates are present only in the 30 in. horizon. The data for the composition of the clay fraction are:

	0–15 in.	*15–30 in.*	*30 in.*
SiO_2/Al_2O_3	2·54	2·37	5·39
SiO_2/R_2O_3	1·85	1·85	3·90
Al_2O_3/Fe_2O_3	2·70	3·59	2·62

The colour of soils of this class is sometimes very vivid, as in parts of South Wales, and it seems reasonable to conclude that they have affinities with the *terra rossa* of Mediterranean regions.

A characteristic feature of soils derived *in situ* from Carboniferous Limestone is the sharp transition from soil to rock. In some cases it is impossible to distinguish more than a single soil horizon, particularly when the mineral colour is sufficiently bright to mask the colour of the humus.

5. *Dune soils*

Dune soils occur at various points along the coastline. They are generally uncultivated and probably find their best use as golf links. It is, perhaps, worthy of note that considerable areas of sandy soil in the dune areas are characterized by wetness associated with a high water-table. This sometimes offers the possibility of successful cultivation. For example, a soil on the south coast of Anglesey, containing over 90 per cent. of coarse sand, carries a group of small-holders whose principal

products are carrots and potatoes. The growth of such crops is rendered possible by the presence of a water-table at about 3 ft. below the surface.

B. *Soils with Impeded Drainage*

These are of very widespread occurrence in Wales. Probably more than half of the area is occupied by soils showing some degree of drainage impedance. The proportion is higher in the wetter regions of the north-west than in the drier area along the English border.

1. *Permanent ground-water soils*

Soils having a permanent water-table sufficiently near the surface to affect the soil profile are found in alluvial flats and bottoms. They are of comparatively limited extent, and are not generally under cultivation. In this class we may place the estuarine alluvia, which, however, show comparatively little profile development.

An example of an alluvial ground-water soil is given by a profile at Ffriddoedd, near Bangor. It occurs under permanent grassland at an elevation of 200 ft. The mean annual rainfall is 40 in., and the parent material is local drift, originating from igneous rocks.

The profile is as follows:

0–5 in. Dark grey silty loam.

5–12 in. Grey to brownish-grey, mottled brown heavy silt loam with water at 12 in. (April 1934).

The analytical data are as follows:

	0–5 in.	*5–12 in.*
Organic carbon . . .	6·26	1·64 per cent.
Clay	22·6	29·2 ,,
pH	5·4	6·1
Clay fraction: SiO_2/Al_2O_3 .	2·85	2·88
,, SiO_2/R_2O_3 .	2·46	2·44
,, Al_2O_3/Fe_2O_3	6·35	5·58

The estuarine alluvia in many cases represent land reclaimed from the sea, for example Sealand in Flintshire, Morfa Mawr in Caernarvonshire, Malltraeth in Anglesey, and the Wentlloog Flats in Monmouthshire. The heavier types are generally in grass of variable quality; the lighter types are in some cases under cultivation, for example the fertile sandy silt of Sealand.

2. *Seasonal ground-water soils*

These occupy the greatest extent of all the impeded-drainage types. They occur in upland situations on gentle slopes, generally near the valley bottoms but often at higher levels also. The parent material is generally boulder clay, but downwash material can also give rise to this soil type. Agriculturally they vary considerably. Where impedance is comparatively slight, or where improvement has been effected by pipe drainage, very fertile soils may occur. They are more suited to grass-land than to arable cultivation.

As an example of this class, a profile from Bryngof, Llanfairpwllgwyngyll.,

Anglesey, may be quoted. The elevation is about 100 ft., the mean annual rainfall 38 in., and the vegetation permanent grass.

The profile description is as follows:

0–10 in. Greyish loam.
10–20 in. Greyish mottled brown micaceous loam.
20–30 in. Grey and brown mottled micaceous heavy loam.

The following analytical data were obtained:

	0–10 in.	*10–20 in.*	*20–30 in.*	
Organic carbon . . .	3·6	0·8	1·4	per cent.
Clay	20·7	15·7	14·3	,,
pH	6·9	8·0	8·0	
Clay fraction: SiO_2/Al_2O_3 .	2·50	2·63	2·66	
,, SiO_2/R_2O_3 .	2·05	1·99	2·02	
,, Al_2O_3/Fe_2O_3 .	4·53	3·11	3·15	

This profile may be compared with the brown earth profile from the same farm (p. 268). It will be noticed that the base status, as shown by the pH, is appreciably higher than that of the well-drained soil. The high pH values for the subsoil horizons are somewhat untrustworthy through the presence of manganese dioxide; but the reaction is definitely alkaline. The sharp decrease in organic carbon below the surface horizon is characteristic for impeded drainage types, and is probably due to the restriction of root-development. The figures for the clay fraction show a slight downward migration of ferric oxide.

3. *Peats*

Although considerable areas of peat occur in Wales no intensive studies have been made of them. The soil survey has, up to the present, been confined mainly to agricultural lands, and these have presented sufficient problems of interest. The peat soils appear to be similar to those studied in other parts of Britain.

(*a*) *Bog Peats.*—The character of the surface of the country is such that extensive areas of bog peat are unusual. The largest single area is probably that occurring near Tregaron in Cardiganshire. Smaller areas occur in Anglesey, Caernarvonshire, and in parts of Central Wales. Although they have not been closely studied, they appear to show the normal features of peats formed from the filling in of former lakes. Fen peats developed in association with waters rich in lime are uncommon, but an example has been found in Anglesey.

(*b*) *Mountain Peats.*—There are extensive areas in the mountain regions occupied by peat overlying local glacial drift and downwash material. They owe their existence to the continuous percolation of surface waters maintaining permanently wet conditions, or to the holding up of percolation by impervious boulder clay.

Conclusion

The soils of Wales are of special interest because all the factors in soil formation, namely, parent material, climate, situation, and human interference have taken part in their development. Thus, whilst the humid

equable climate of Wales dominates soil development, important differences between soils can be traced to the influence of parent material. The sharply varying surface-forms also introduce important differences, notably in the water-conditions, whilst, except in the highest lands, changes consequent on agricultural and pastoral development have produced profound modifications of the original soils.

No soil map of Wales is shown in connexion with the present paper. Although most of the classes of soils likely to be found have been already studied, detailed mapping has only been extended over the agricultural lands of a few counties. Apart from this, however, the distribution is so intricate that a small-scale map could scarcely give even an approximate idea of the soils of a country where, owing to the character of the surface, it is quite usual to find two or more distinct types of soil in the same field.

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BIRDSFOOT TREFOIL IN AGRICULTURE

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IN these islands the seed of Birdsfoot Trefoil (*Lotus corniculatus*) is seldom sown as a crop, but on the Continent, and particularly in parts of France, the plant has a good reputation on the poorer types of soil.

The type indigenous to the British Isles is of a dwarf, more or less prostrate nature, whilst that cultivated on the Continent has narrower leaves and a more erect habit. The first is essentially a grazing plant, whilst the second is said to give considerable yields of hay in a suitable season. These types have recently been described by Robinson [1] and there is no need to go into details here; but in view of the enthusiastic way in which certain French writers advocate the extended use of birdsfoot trefoil it may be useful to give a summary of the more important literature dealing with the species, treating it particularly from an agricultural standpoint. An exhaustive account of the anatomy, classification, and economic uses of the various species of birdsfoot trefoil is given by Robinson in an unpublished thesis presented to the University of London, and upon this the present paper is based.

Several continental writers on agriculture, for example, Stebler and Volkart [2], Witte [3], Lesourd [4], and Hegi [5], give the credit for bringing the plant to the notice of agriculturalists to Worlidge, citing his *Systema Agriculturae*, published in 1681. In this I think they are wrong, and for the following reasons. They state, for example, that Worlidge classed birdsfoot trefoil amongst esparcet (sainfoin), French tares or vetches, spurrey, and even clover and lucerne. From this statement it is clear that the plant which they identify as *Lotus corniculatus* is that described as follows by Worlidge (loc. cit., section v, p. 32, ed. of 1681): 'Hop Clover, Trefoyle, or Three-leaved Grass, is both finer and sweeter than the great Clover-grass; it will grow in any ground: it may be sowen with Corn (as before) or without, or being sprinkled in Meadows, will exceedingly mend the hay, both in burthen and goodness.'

From this account it is not easy to understand why this 'Trefoyl' is identified as *Lotus corniculatus*. The flower heads of birdsfoot trefoil have not the least resemblance to those of the hop, and it is much more likely that the plant Worlidge had in mind was *Medicago lupulina*, or perhaps *Trifolium minus*. If, however, Worlidge's plant be accepted as birdsfoot trefoil, then the date when it was first mentioned as a crop plant must be put back twelve or thirteen years. The identical statement regarding 'Trefoyl' appears in the first edition of *Systema Agriculturae* (p. 29) published in 1668; the edition dated 1681 is the third edition.

The first writer to give any useful account of birdsfoot trefoil was William Ellis [6], who farmed at Little Gaddesden, near Hempstead, in Hertfordshire. With his customary enthusiasm he stated that 'There has been no Exotic Grass seed ever yet imported that is near so fine and serviceable as this native sort. . . . (It) will feed all sorts of Cattle fat in

a little Time, make the sweetest of Fresh Butter and Cheese, and give the last two the finest golden Colour. . . . It is justly deemed the most delicate Grass that grows in England. . . .'

Anderson [7] in 1777 thought that 'the greatest bar to the cultivation thereof will be the difficulty of obtaining the seeds in abundance, as . . . they must always be gathered by hand'. Marshall [8] in 1785 inquired 'might not a productive variety of this plant be cultivated with profit, in dry burning situations?'

Withering [9] in 1776, probably taking Ellis's writings as his authority, said 'In Hertfordshire it is cultivated as pasturage for sheep'. Arthur Young [10], however, stated that although he had been all over the county he had never seen birdsfoot trefoil cultivated.

Smith [11] and Martyn [12] referred to the agricultural possibilities of the plant. Sinclair [13], about 1826, estimated the produce of the plant at the time of flowering as just under four and a half tons per acre, but he considered the taste too bitter. Lawson [14], Low [15], and Morton [16] make only brief mention of birdsfoot trefoil. The last stated that its nutritious qualities were probably equal to those of clover.

In France, birdsfoot trefoil received less attention than in England during the sixteenth and seventeenth centuries. The credit for first recommending the plant to agriculturalists is always given to the English writers by the French authorities.

According to Lesourd [4], the first Frenchman to draw attention to birdsfoot trefoil was Cretté de Palluel, writing in 1787 and later in 1805. The precise time, however, when it was first cultivated in France is not known. From Lesourd's account one gets the erroneous impression that birdsfoot trefoil was being cultivated extensively in the county of Hereford (*sic*) at the end of the eighteenth century.[1]

Leclerc-Thouin [17], Lecoq [18], Vianne [19], and Vilmorin [20] all have a good word for the species. We read [4] that about 1892 a certain M. Martin, of St. Paul-des-Landes in Cantal, began to use birdsfoot trefoil for temporary meadows; by 1905 he had 61 acres of land devoted exclusively to it.

Stebler and Volkart state that the culture of the plant in Switzerland began about 1865. In Italy, according to Lesourd, its culture began about 1880.

Cultivation for Fodder

The cultivation of birdsfoot trefoil for fodder may be desirable where soil and other conditions give it an advantage over other crops. For example, Rothschild [21] has described a case where a satisfactory stand of this species was obtained upon an impervious, badly drained soil where grassland of the ordinary type was impossible. Taussac [22] has given an account of a somewhat similar case in the valleys of the Arnette, Larn, and Thoré, where, because of the shallow soil and the nearness of the water-table to the surface in winter, the growing of lucerne is impossible. Here again birdsfoot trefoil has been satisfactorily used.

[1] See letter from author under title 'Le Lotier corniculé en Angleterre et en France' in *Journal d'Agriculture pratique*, 29 juillet, 1933, No. 30, p. 91.

Schribaux [23] has pointed out that birdsfoot trefoil will do well on land which for various reasons does not support red clover or lucerne. It may be that the soil is too poor, too dry, or lacking in lime. It may be infected with the seeds of Broomrape (*Orobanche* spp.) or of Dodder (*Cuscuta* spp.), which seldom parasitize birdsfoot trefoil; or the soil may be clover- or lucerne-sick, owing either to *Rhizoctonia* or eelworm infection; or perhaps conditions are such that clover or lucerne lose a lot of leaves during hay-making. In these circumstances birdsfoot trefoil is worth a trial.

Floderer Sándor [24] says that the two most profitable plants on alkaline soils are *Lotus corniculatus* and 'fodder beet'. In very alkaline soils he states that the factor determining the success or failure of both lucerne and clover is not the total amount of salts present, but the proportion of soda. He showed that the presence of 0·02 per cent. of soda in the soil at a depth of between 30 and 60 cm., and a mere trace at 60–90 cm. was sufficient to cause the failure of lucerne. Clover failed when the proportions at similar depths were 0·05 per cent. and 0·08 per cent. respectively. On the other hand, birdsfoot trefoil grew well in soil having 0·19 per cent. soda at 30–40 cm., plus a further 0·1 per cent. soda at 90–120 cm.

Most of the published data concerned with birdsfoot trefoil relate to the narrow-leaved type. In only one or two countries is the plant sown as a self-crop, namely, in certain parts of France, notably the Central regions, and according to Laplaud [25], in Algeria. It is claimed that the 'Lotières', or areas devoted exclusively to birdsfoot trefoil, give results comparable to similar areas devoted to lucerne, the so-called 'Luzernières'. Sagnier [26] says that in wet soils they give excellent results, and in dry soils provide returns which cannot be obtained with any other legume.

In the making of a Lotière, seed is sown under oats or barley. If drilled, the rows are commonly between 4 and 8 in. apart, and the seed rate is from 9 to 12 lb. per acre. When broadcast, from 10 to 18 lb. of seed are required. This comparatively low rate of seeding is put forward as an additional point in favour of birdsfoot trefoil, because in spite of the high price per pound of its seed, the actual cost per acre of a seeding is less than that of a mixture of red clover and grasses, or of lucerne.

Cultivation alone is not recommended except in unusual circumstances. Not only is there a tendency to lodge but, if broadcast without any provision for inter-cultivation, there is a danger that the land may become weedy. Lindhard [27], in some experiments on this point at Tystofte, found that *L. corniculatus* sown alone gave a crop containing 22 per cent. of weeds. When species of *Poa* were mixed with the seed the percentage of weeds was reduced to eight, and using a mixture of three different species of grass it was reduced to two.

The usual method of cultivation is with an admixture of grasses, which not only support the plant when established, but cover the ground in the early stages and keep out weeds. Lindhard [28] considers that birdsfoot trefoil is of little importance where other, rapidly growing legumes are included. He suggests that it should be mixed only with grasses that are likely to stand well during the second, third, and fourth years.

Where only one grass species is used for supporting birdsfoot trefoil, the following additions have been suggested [29], using in every case a basal quantity of 10 lb. of birdsfoot trefoil seed per acre. In medium to good soils, 6–7 lb. cocksfoot; in moist soils, 9–10 lb. meadow fescue; in dry soils, 9–10 lb. *Bromus erectus*.

Taussac [22] recommends a heavy admixture of perennial rye-grass, giving as a suitable combination 9–11 lb. birdsfoot trefoil and 35–40 lb. rye-grass per acre. If grown especially for feeding horses the rye-grass should be replaced by cocksfoot.

For wet soils a mixture of 7 lb. *L. corniculatus* and 7 lb. *L. major* has been suggested [23]. From the same source comes a recommendation to mix 3 lb. birdsfoot trefoil with sainfoin.

Where it is not desired to rely entirely upon one grass species the following prescriptions, reduced to lb. per acre, may be utilized [30]:

	Medium soils	*Medium to good*	*Medium dry*	*Very poor, calcareous*
Birdsfoot trefoil	9	7	9	9
Cocksfoot	7	7	2–3	2–3
Tall oat-grass	..	7	9	..
Bromus erectus	..	..	13	13
Perennial rye-grass	5	..	..	5
Smooth meadow-grass	1–2	..	..	..

The success of the crop depends to a considerable extent upon the supplies of potash and phosphates in the soil. Given a sufficiency of these two plant-foods the crop is capable of yielding well for a long time, periods of 9–20 years being not uncommon. For enriching the soil before sowing the following dressing may be taken as adequate: 4 cwt. sylvinite or 1 cwt. chloride of potash, plus 4–8 cwt. basic slag or 4 cwt. superphosphate.

Birdsfoot trefoil grows successfully upon land deficient in lime, but Lindhard [28] traces a direct relationship between the lime-content of a soil and the establishment thereon of the plant. In some experiments carried out at Hannerup the number of plants which established themselves per hundred viable seeds sown was, on a lime-poor soil 37, and on a lime-rich soil 47.

The usual time for sowing is in the spring, but in parts of Germany where dry springs are to be expected Becker states that autumn sowing is to be preferred. Most authorities recommend a nurse crop, usually oats, sometimes barley. A two-thirds seeding of the cereal is sufficient: this avoids excessive shading of the legume. It is advisable to delay sowing until there is little danger of frost when the seedlings are coming through the ground.

Taussac, in a detailed description of the method of establishing a meadow based upon a heavy seeding of birdsfoot trefoil, recommends sowing the seed at the same time as the cereal. He advises sowing the oats with a disk drill, following with the rye-grass broadcast by hand, after which a light harrow is run over the land. Then comes the birdsfoot trefoil seed, broadcast, followed by the roller. In this way the oats and

rye-grass, both comparatively large seeds, are adequately covered by the harrow, whilst the small seeds of the legume are merely pressed into the fine surface soil where their peculiar conditions for germination are satisfied.

Numerous writers emphasize how essential it is that seed of this plant should not be deeply covered by soil: if the roller is unsuitable for covering the seed, the use of a bush harrow is advised.

Lindhard [28], in describing some small-scale experiments carried out at four different centres in Denmark, found that birdsfoot trefoil germinated about as well as red clover and gave about as many plants in the first harvest year. Its persistence, however, was superior to that of red clover. For every 100 viable seeds sown there were in the first seeding year 71 plants of birdsfoot trefoil, in the first harvest year 42 plants, in the second harvest year 42 plants, and in the third harvest year 21 plants. In the second and third harvest years there were only 14 and 5 plants respectively of red clover per 100 viable seeds sown. The tests were hardly on a sufficiently large scale to be regarded as conclusive.

Rolling when the oats are 4–6 in. high is recommended by Schribaux. After the nurse crop has been removed the ley must be treated carefully that it may establish itself firmly. Grazing must not be permitted until the root-development is such that the plants can recover after defoliation. In the first harvest year the first crop should be mown and the second grazed.

Yields are variable and depend upon the soil and climatic factors. Taussac says that a well-established birdsfoot-trefoil ley will give at its first cut almost as much as lucerne, but that subsequent cuts are much less bulky. The total yield of green fodder obtained from two or three cuts in the season has been variously estimated at from 6 to 15 tons per acre. Laplaud [31] says that as many as four cuts may be obtained in a favourable season. The usual plan is to take one, two, or possibly three cuts, following up with grazing animals.

Laplaud gives, as the minimum quantity of dry fodder which may be expected from a Lotière, 28 cwt. from the first cut and 12 cwt. from the second cut. A certain M. Louis Martin, of Saint-Paul-des-Landes (Cantal) is reported to have obtained over four tons of dry fodder per acre from an area devoted exclusively to birdsfoot trefoil, made up of nearly 49 cwt. at the first cut in June, and 36 cwt. at the second cut in September.

Nielsen [32], describing some trials in Denmark, showed that under the conditions obtaining at four different centres, the narrow-leaved form gave a higher yield of hay over two harvest years than Silesian early red clover. The clover yielded more heavily in the first harvest year in the proportion of 100 to 98, but when the total amount of hay for the two harvest years was considered there was a difference of 31 per cent. in favour of the trefoil.

Nielsen also reported some comparative yields of birdsfoot trefoil and lucerne. On three fields at Tystofte, birdsfoot trefoil gave a smaller yield of hay than lucerne over a period of three years, whilst at Askov on two fields the positions were reversed, the trefoil showing a substantially

higher yield than lucerne. The figures for the two centres are shown below, the yield of lucerne being taken as 100 in each case.

Comparative Yields of Birdsfoot Trefoil and Lucerne (= 100)
Harvest Years

	1st	*2nd*	*3rd*	*Total*
Tystofte . .	180	76	49	84
Askov . .	150	113	127	129

The amount and kind of grass seeds with which the trefoil is mixed have an effect on the yield. Lindhard states that in general there is an increase in yield with increase in the amount of trefoil seed sown, and a decrease in the amount of grass seed sown. This, he concludes, is due in part to the thicker plant secured.

In his experiments birdsfoot trefoil was sown alone at the rate of about 14·5 lb. per acre, and also at the rates of 6, 9, and 11·5 lb., mixed with varying amounts of grass seed. The species used were cocksfoot, tall oat-grass, timothy, and *Poa fertilis*. The average yields of hay per acre for the different quantities of seed for each mixture, and the proportion of birdsfoot trefoil in the hay of each are shown in the table below:

	Hay	*Trefoil in hay*
	cwt. per acre	per cent.
Birdsfoot trefoil alone . .	92	78
With tall oat-grass . . .	103	30
With *Poa fertilis* . . .	89	58
With timothy . . .	88	43
With cocksfoot . . .	73·5	36

Phosphatic manures greatly stimulate birdsfoot trefoil, and produce results similar to those obtained with wild white clover. Stapledon [33] and Somerville [34] record great increases with phosphatic manures in the south of England.

There is evidence to show, however, that where birdsfoot trefoil occurs somewhat thinly in a turf, heavy manuring tends to reduce it. At Rothamsted [35], on the plots which for many years have been manured and cut for hay, birdsfoot trefoil has almost always been most abundant on the unmanured plot. Under nitrogenous dressings the plant is completely extirpated. Stapledon says that at Cirencester the unmanured plot easily contained the most birdsfoot trefoil—6·9 per cent.—but that of the manured plots those receiving nitrogen showed the next highest amount, namely, 3 per cent. with sulphate of ammonia alone, and 3·1 per cent. with nitrate of soda and kainit. These discordant results are probably due to the fact that at Rothamsted all the produce was removed as hay, whilst at Cirencester only the first crop was cut, the subsequent growth being grazed.

Christensen [36] found that when grazing only was practised the allied species *Lotus major* constituted 11 per cent. of the leguminous plants present, whilst where cutting alone was carried out the proportion fell

to 4 per cent. Even where grazing followed cutting, the leguminous plants constituted only 5·8 per cent. of the total herbage, as against 19·7 per cent. after grazing alone.

Könekamp and König [37] have shown that birdsfoot trefoil rapidly disappears from a turf which is artificially watered, and also if it is heavily stocked with sheep with infrequent rest-periods.

There seems to be a fairly general agreement amongst agricultural writers that birdsfoot trefoil provides a palatable fodder. Ellis, Anderson, Vianne, Sutton, and Schribaux all praise it. According to Sinclair, it was the opinion of Linnaeus that sheep and swine are not fond of it. Laplaud says that in spring sheep do not touch it, but that later, during droughts, this plant alone remains green and is then eaten. Against this, Schribaux says that sheep dote on it more than cattle, and that rabbits prefer it to lucerne.

It seems likely, therefore, that the palatability of the plant may vary from one district to another, possibly on account of soil differences and the density of the hairs on the stem. It is claimed that birdsfoot trefoil will never 'hoove' or 'blow' sheep or cattle.

Stebler and Volkart, and also some French writers, assert that the intense yellow of the flowers passes into the milk of cows consuming them, and to the butter made from such milk. Schribaux says, on the contrary, that the flowers are frequently refused by stock, and to this he attributes the liberal manner in which the plant naturally re-seeds itself, thus assuring permanency. The reason he gives for this rejection, namely, the presence of a cyanogenetic glucoside, is probably incorrect, since all parts of the shoot contain this glucoside and are nevertheless eaten.

The analysis of birdsfoot-trefoil hay is shown in the following table. The figures are averaged out from those prepared by Kellner-Fingerling, Honcamp, and Garola (all of which agree very closely), as given by Becker [29], with the exception of those for digestible nutrients, which are based upon the figures of the first two authors only. There was 87·5 per cent. of dry matter in the hay in all cases.

Composition of Birdsfoot-Trefoil Hay

	Protein	*Fat*	*N-free extract*	*Fibre*
Crude. . .	14·4	3·4	39·3	23·0 per cent.
Digestible . .	8·2	1·6	26·7	11·3 per cent.

On these figures the starch-equivalent is between 32·7 and 33·0 per cent.

The ash contains (per cent.): potash, 23·3; lime, 20·8; phosphoric acid, 10·9; and magnesia, 5·2.

Birdsfoot trefoil therefore compares very favourably with lucerne, having rather less digestible protein, but more digestible fat, nitrogen-free extract, and fibre.

Hagemann [38] gives the following coefficients of digestibility of *Lotus corniculatus* hay, at six days, using sheep (per cent.): dry matter, 59·8;

protein, 75·5; ether-extract, 42·9; nitrogen-free extract, 64·3; crude fibre, 48·5; ash, 62·5.

Cultivation for Seed

Several of the early writers on agriculture considered that the cultivation of *Lotus corniculatus* would never become an economic possibility on account of the difficulty of securing enough seed at a reasonable price.

The views of Anderson have already been referred to, and Boitel [39] in 1893 said 'unfortunately its pod opens at maturity and spreads its seed upon the ground. It is therefore impossible to save it in any quantity. Thus one prefers to birdsfoot trefoil other legumes which are not worth less as forage, and whose seed can be obtained more cheaply.'

Witte [40] reports the following average yields of seed from crops in Sweden, grown specially for the purpose during the years 1910–19: birdsfoot trefoil 170 lb., red clover 337 lb., alsike clover 312 lb. per acre.

In France it is generally recommended to take a seed crop after the first has been cut for hay or fodder. It is essential to cut the crop before it is mature on account of the readiness with which the pods split as they ripen. Owing to the irregular way in which pod-formation takes place only a portion of the seeds can be harvested, and experience alone can decide the most advantageous time for cutting. The time of taking the first crop affects the seed-crop. It is recommended [41] that the first cut be made early, at the appearance of the first flowers.

Lesourd advises the collection of the seed plants into small heaps so as to avoid the direct action of the sun, which causes the pods to split. Careful handling is required if losses are to be minimized. Fischer [42] recommends cutting on a dewy morning and carrying in the pods on a sheet.

French authors agree that a yield of from 300 to 400 kg. of seed per hectare (250–350 lb. per acre) may be expected.

It is suggested [41] that a soil of low fertility, but strongly enriched with potash and phosphates, gives the best results. On dry soils the tallest plants have a tendency to lodge, bear fewer flowers, and flower at longer intervals than on moister soils. There is thus a tendency for less seed to be produced, and the irregular maturity of the pods increases the likelihood of losing the best seed from the flowers first formed.

In Denmark, where the climate differs considerably from that of the districts in France where birdsfoot-trefoil seed is grown, yields and cultural methods are not the same. Lindhard and Bagge [43], in reporting the results obtained at different experimental centres between 1908 and 1910, stated that the plant gave the highest seed yields from comparatively thin seedings. They recommend the sowing of 4–6 kg. of seed per hectare (4·5–6·5 lb. per acre) in drills 30 cm. apart, or broadcasting 6–9 kg. per hectare.

In the experimental plots of 125 sq. m. in area an increased rate of seeding diminished the yield of seed but increased the hay. The authors recommend taking seed at the first cut, not only because of the greater quantity obtainable, but also because of the poor quality of late harvested seed. The superiority of the first cut during the first harvest

year is shown by an average yield of 269 kg. per hectare, as compared with only 86 kg. from the second cut in the first harvest-year. Less seed was shed when the plants were bound in sheaves and set up in small heaps than when they were cured in swathes.

In Denmark cold wet weather, which may occur during flowering, extends the length of this period considerably. There is also danger of attack by aphis at the beginning of June, before the flowers expand. There is consequently a tendency for seed-production to diminish in that country, reliance being placed on imported seed, which is generally better than the home-grown material.

In Germany Fischer [42] recommends the sowing of 7–11 lb. of seed per acre in drills 10–14 in. apart. The usual time to sow is in spring, under a corn crop. The seed may also be dibbed in, each plant being allowed an area of about one sq. yd. He prescribes for seed-culture a mixture of 9 lb. birdsfoot-trefoil seed and about 2 lb. timothy per acre, the grass assisting to support the weak stems of the legume. He says there is no difficulty in separating the two seeds after harvest, a purity of 98 per cent. being readily obtained for both species. He gives the average yield as 90–270 lb. per acre.

Fischer also recommends using the first cut, but in a wet spring a hay-cut can be taken in the middle of May and a seed-crop at the beginning of September. He suggests cutting when the earlier formed pods begin to turn violet or brown, and while the plants are still green.

Threshing is a simple operation, but Fischer states that newly threshed seed is very liable to go mouldy. It should therefore be spread out in thin layers on a level floor, and be repeatedly turned until dry. Schribaux says that the straw after threshing makes good fodder.

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